PB-217 037

WASTE WATER LAGOON CRITERIA FOR MARITIME CLIMATES

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Corvallis, Oregon

1 July 1965

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Final Report

WASTE WATER LAGOON CRITERIA FOR MARITIME CLIMATES

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July 1, 1965

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WASTE WATER LAGOON CRITERIA FOR MARITIME CLIMATES

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I. SUMMARY

Waste-water Oxidation Lagoon studies were conducted at Oregon State University in an effort to establish criteria for their use in the maritime climate of the Pacific Northwest. The study was instigated with assistance of the State Sanitary Authority, the League of Oregon Cities, the City of Corvallis and several consulting engineers who saw a possible economical solution to the treatment of waste water with the use of lagoons. The study was then continued for a period of five years with support from the Public Health Service through a National Institute of Health grant.

Facilities for this study consisted of two cells three feet deep and each having a surface area of one acre. Support facilities such as pumps, recorders, laboratory facilities and small river and lagoon models were used on certain phases of the study. Waste water which was pumped to the lagoon was obtained from the Corvallis Municipal Sewage Treatment Plant at a point following the comminutor and before the point of disinfection. Operating procedure included both single unit and two unit series operation.

Lagoons as described in this report were operated as units in which all treatment of waste water resulted from naturally occurring phenomena. No aids to treatment such as mechanical mixing, or chemical addition, were employed.

Criteria for unacceptable operation was offensive odors associated with anaerobic condition. Indicators of deteriorating condition included poor color, floating sludge, tubifex at water's edge and declining pH.

Threshold loadings at which offensive odors were detected were as low as 50 pounds of five-day BOD per acre per day. Poor color, floating sludge and tubifex at water's edge were observed at loading values of about 20 pounds of five-day BOD per acre per day during critical periods in September and October.

BOD removals from primary, single, aerobically operated units were found to be about 80 per cent. When two cells operated in series were employed loaded at rates in which the primary cell remained aerobic, the BOD removal in the secondary cell ranged from a high of 50 to a low of 20 per cent of that BOD being applied to the secondary cell. BOD removals were found to drop to as low as 23 per cent when anaerobic conditions existed in the primary cell.

Reduction of coliform organisms which were used as an indicator of fecal coliforms was found to vary from 50 to as high as 99.5 per cent with loadings where aerobic conditions were maintained. Model studies using a series of four units indicated that low reduction values were possibly a result of short circuiting.

Disinfection requirements to maintain a 0.5 mg. per liter residual at 30 minutes detention time were found to vary from a low of 1.0 to as high as 16 mg. per liter. It was of interest to note that at periods of failure or poor condition, effluent chlorine requirement at times were greater than the chlorine required to disinfect the influent.

In operating four cells in series similar end results as to coliform reduction and BOD reduction were found regardless of the point of application of chlorine for disinfection purposes. Advantage was found to exist in the chlorine required for disinfection when chlorine was added late in the series.

Inspection of sludge build up by sampling revealed that sludge build up amounted to approximately six inches as a maximum with the greater portion of undigested sludge lying at the end of the inlet pipe. Upon draining the lagoon undigested sludge was shown to exist at that depth of approximately six inches for about 80 feet from the end of the inlet pipe with a width of about 40 feet.

Around the area of sludge build up, material appearing to be well digested sludge and dead algal cells was observed at a depth of not greater than one and one-half inches.

Loss of water through dykes and the bottom was observed at several lagoon sites. This, at some locations, resulted in water levels so low that aquatic weeds were not controlled nor was the level great enough to maintain proper "working" conditions.

The three-foot level was found to be the most effective "working" depth and depth for controlling aquatic weeds. This depth could have been maintained in most cases with some earth or soil preparation, depending on soil conditions. Where depths of three feet or more were maintained it was found that aquatic weeds other than those growing at the water's edge were eliminated. To control these marginal weeds, spraying and mowing were found effective.

It was found that control of aquatic and marginal weeds and thus eliminating the mosquito's breeding place was the most effective way to control mosquitos. Even with this effort, however, it was necessary at certain times during the summer months to kill mosquito larva by spraying.

The introduction of Gamlausia affinis, a small surface feeding fish, was found to be ineffective as a means of mosquito control.

Oxygen necessary to satisfy the needs of waste decomposition in an aerobic environment comes from two sources. Algal produced oxygen accounts for the greater part while oxygen from aeration accounts for a minor but important portion.

Algal activity and algal oxygen produced is light energy dependent. Values were found to range to well above the saturation level in the upper 6" portion of the lagoon during summer days of high solar energy. During low solar energy days or during the hours of darkness dissolved oxygen values were found to a fraction of one milligram per liter at what time aerated oxygen played a more important role.

Analysis of test results showed the best data correlation existed in comparing the organic load of influent to effluent. This comparison indicated that about 80 per cent of organic loading removal could be expected over a range of loading from 20 to 150 pounds of five-day BOD per acre per day. The stated criteria, however, for acceptable operation was odor free operation and odors associated with anaerobic decomposition were detected at loading as low as 50 pounds of five-day BOD per acre per day. In keeping with good engineering practice a loading of 35 pounds of five-day BOD per acre per day was accepted as maximum. This organic load would equal that produced by approximately 200 persons.

In a characteristically maritime climate yearly precipitation exceeds evaporation, therefore, an effluent will discharge from a lagoon. If a multi-use concept of the receiving stream includes recreational use during the summer, there may be certain advantages in storing or not discharging during the four summer months from June through September when low steam flows are occurring.

Storage necessary, inflow less evaporation, calculated on the basis of 200 persons per acre and 100 gallons per capita per day was found to be 5.35 acre feet. This suggested that a lagoon with dykes that would hold water to a depth of approximately 8 feet would be adequate to eliminate the need for discharging during the summer months.

Cost comparison was made for treating waste considering lagooning, conventional primary treatment and primary plus secondary treatment processes. Initial per capita cost for lagooning wastes at rates of 20 pounds of five-day BOD per acre per day, which is approximately one-half the loading rate considered maximum, were found to be less than the cost of primary treatment facilities. Added costs for additional necessary storage when allowing no outflow during the four months, May through September, were found to make initial lagoon costs to be approximately equal to initial primary treatment plant costs.

II. INTRODUCTION

This report has been prepared to describe a waste water oxidation lagoon study conducted at Oregon State University. The study was instigated in an effort to better understand biological, chemical and physical mechanisms involved in the stabilization of organic wastes in oxidation lagoons operating in maritime climates. Because the practical necessity of applying lagoons to waste treatment was most pressing, a more specific objective was to establish criteria for design and operation of aerobic lagoons in the maritime climate of the Pacific Northwest. Assistance in initiating the study was provided by the State Sanitary Authority of Oregon, the League of Oregon Cities, the City of Corvallis, and several consulting engineers who believed that oxidation lagooning offered an economical solution to treatment of waste water for many small municipalities, industries and new residential developments.

Experimental field facilities consisting of two cells, each one acre in surface area and approximately three feet deep, were operated for the greater part of this study. Five additional field units, each approximately 200 square feet in surface area and three feet deep were constructed for series operation and soil sealing studies. Additional laboratory models on which more precise control could be maintained were used for certain phases of lagoon studies where such control was necessary. Observations from existing facilities throughout the state were made and have been included where applicable.

Significance of this Research

The use of oxidation lagoons as an economic solution to the treatment of domestic and certain industrial wastes in the maritime climates of the Pacific Northwest is dependent upon the establishment of loading criteria, operational procedures and the solution of some of the related problems. Many of the problems are common to any location and much research has been done. Other problems, however, are regional in character and are affected by climate and waste characteristics. In maritime areas, annual precipitation exceeds evaporation, which results in effluent from a lagoon. It is necessary, therefore, that bacteriological quality and disinfection requirements of the effluent and its effect on the receiving stream be evaluated in establishing lagoon feasibility. Low light intensities and long cool rainy periods during the winter months make studies of sludge accumulation, sludge degradation, oxygen reaeration and algal respiratory requirements assume added importance. Factors contributing to odor and mosquito nuisance control must be considered in selecting lagoon size and location.

Lagooning offers an economic solution for the treatment of many industrial wastes. However, because of high color and low light penetration for many of these waste waters, photosynthetic production of oxygen by algae is limited even during summer months. Reoxygenation of lagoons under these conditions must be largely from surface sources. Hence, studies of reaeration mechanics and development of experimental methods for determining reaeration constants are important.

The Pacific Northwest maritime area is characterized by winters of high rainfall and low light intensity (See Table 3, page 43). Summer periods, however, are characterized by prolonged dry periods, and many streams available for effluent dilution have very low or minimum flows. Studies of evaporation and water balance in lagoons and interpretation of the effect of effluent quality on receiving streams during these periods are of major importance. In many areas, ground water contamination is a problem which requires information on seepage rates and soil sealing.

Contributors

The initial project was undertaken in 1958 at the suggestion of representatives of the Oregon State Sanitary Authority, municipalities, and consulting engineers. Construction of the test facilities was accomplished under a grant of $5,875 provided by the Oregon State Sanitary Authority. A single cell lagoon having a surface area of approximately two acres was completed in the fall of that year and studies during the winter of 1958-59 were conducted by Mr. Gerald Whitney, graduate student, while being supported on a U.S. Public Health Service Traineeship. Studies conducted during the summer of 1959 were financed by the Oregon State University Engineering Experiment Station and conducted by Mr. Thomas L. Miksch. Support for three years of study was received from a Public Health Service National Institute of Health research grant on December 1, 1959 and extended for an additional two years on December 1, 1962. Much has been contributed in the way of labor, materials and the lagoon site by the City of Corvallis, Oregon, without which this project would not have been possible.

Description of Experimental Facilities

The experimental lagoon facility was located 600 feet north of the Corvallis, Oregon Sewage Treatment Plant. The primary test unit consisted of two cells, each 1.07 acres in surface area. Although liquid depth adjustment was possible, all research was conducted with a depth of three feet. Dikes enclosing the unit were eight feet across the top and had a side slope of two horizontal to one vertical. Six inch fiber pipelines extended to a discharge point at the center of each cell. Control facilities permitted parallel cell loading at different rates under the same conditions, or series loading. Outlets from each cell were located on the south dike and discharged into a drainage ditch. Permanent stations (See Figure 1) for studying sludge accumulations and bacteriological conditions were referenced to permit comparative studies over a period of time. Five small cells, each 200 square feet in surface area were constructed adjacent to the south dike of the lagoon to permit studies on the effect of chlorination on lagoon operation, soil sealing, and series operation with extended detention periods.

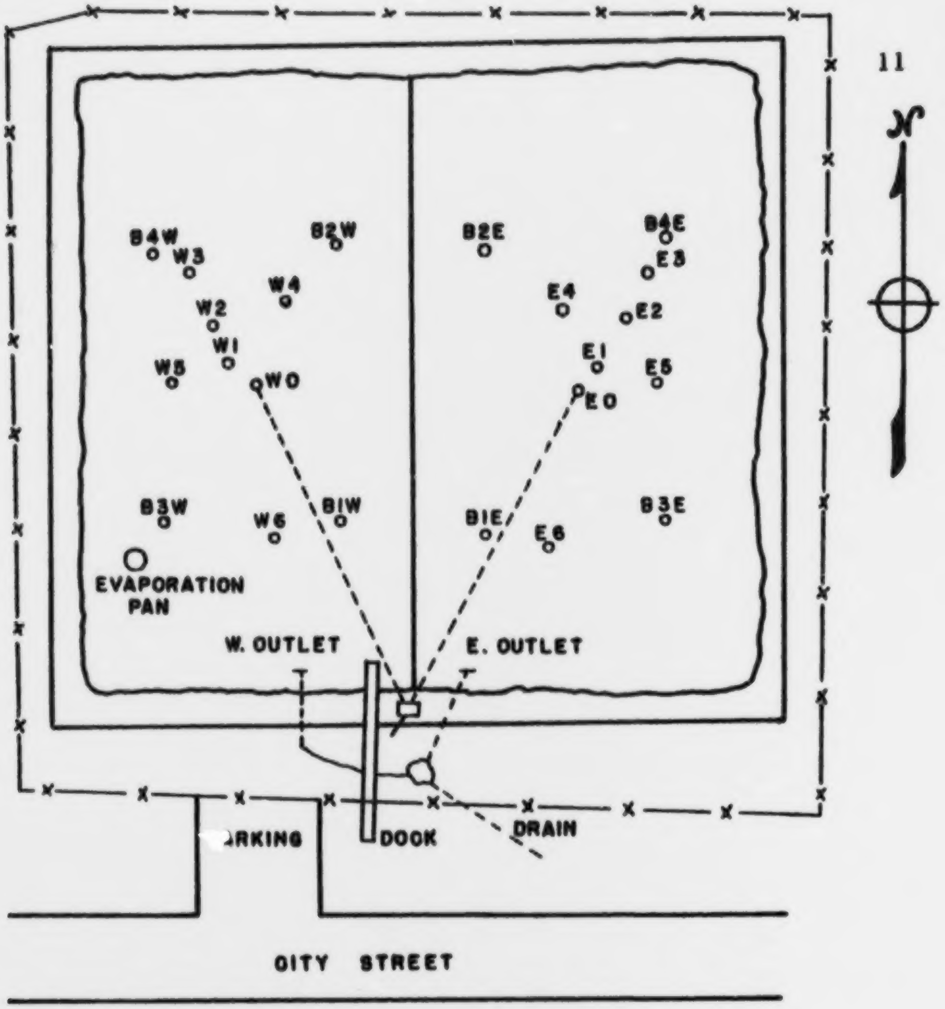
The lagoon facility was enclosed by a five-strand barbed wire fence. Suitable signs (See Figure 2) indicating the nature of the study and warning the public as to the lagoon contents were displayed on the fence. The lagoon effluent entered an outfall sewer that discharged to the Willamette River. A parking lot, walkways, analysis shelter, docks and two boats served as support facilities.

Control Equipment

Sewage was pumped to the lagoon site by a 350-gpm centrifugal sewage pump. Control of total quantity was accomplished by adjusting pumping time with a time clock system. The pump intake was located on the return elbow of the sewage plant comminuter, thus providing comminuted raw sewage for this study. The pump discharge piping to the lagoon consisted of two four-inch steel pipelines that terminated in a flow measurement box equipped with a seven-day liquid level recorder to provide for continuous monitoring of the system. A water wheel on the measurement box drove a sample compositing mechanism that operated at all times that the pump was running in order to obtain representative samples. Results from tests performed on samples collected by this device, and samples collected by an electrically controlled compositing device at the pump and samples composited by existing facilities at the Corvallis Sewage Treatment plant showed close agreement. Hence, information on raw waste was obtained from samples which were the most convenient to collect from the different points at any given time during the study.

Laboratory

Major testing was accomplished in the Sanitary Engineering Laboratory of the Department of Civil Engineering. Facilities of the Department of Microbiology and the City of Corvallis were used as needed. A shelter was constructed at the lagoon site to serve as a laboratory when immediate analysis of collected samples was necessary. Space for construction and operation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B4E
E3
E4
E2
E1
E5
E0
B1E
E6
B3E
E. OUTLET
ARKING
DOCK
DRAIN
CITY STREET

Figure 1. Oregon State University Experimental Lagoon Plan, Corvallis, Oregon

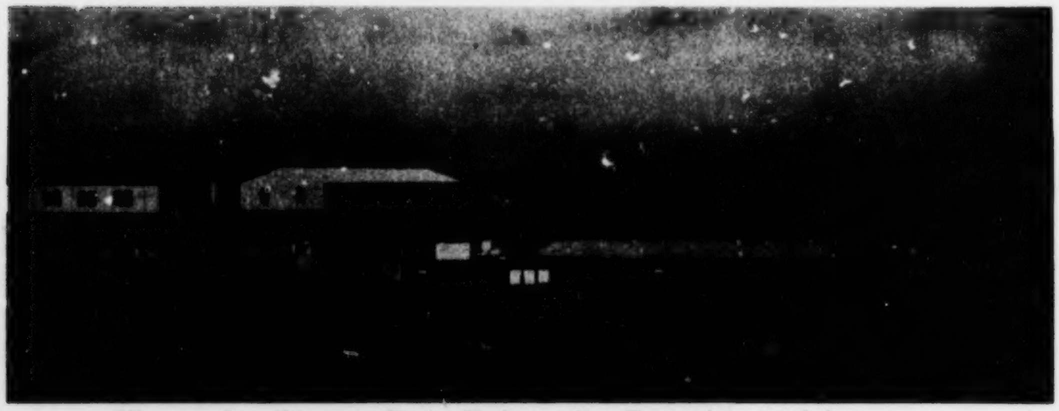


Figure 2. Oregon State University Experimental Lagoon, Corvallis, Oregon

of laboratory models was provided by the Engineering Experiment Station.

Method of Procedure

So that the results of this investigation could fulfill the stated purposes of the study, to provide immediate usable information on loading, and yet help to resolve some of the more basic problems, the research was divided into two experimental approaches. The two-cell experimental lagoon, (See Figures 1 and 2) which is described later in this report, served as the basic facility for testing. Related laboratory work and results from operating lagoons at other locations were used to substantiate findings. Data on loading, influent and effluent quality, and weather were collected routinely and served as the nuclei of the project. Separate studies on re-aeration, disinfection, oxygen production, soil sealing, sludge accumulation, temperature prediction and effects of lagoon effluent on a receiving stream were coordinated with the basic program and served as areas of study for graduate student programs.

III. BASIC LAGOON OPERATION

Loading

Experimental results discussed in this report were obtained from studies of the aerobic waste water lagoon that included two phases. "Phase I" covers that part of the study in which the two one-acre cells were operated in parallel. "Phase II" covers that part of the study in which the two one-acre cells were loaded in series.

The primary measures of loading for this study were flow, five-day biochemical oxygen demand (BOD) and suspended solids (SS). Tests to provide this information were conducted routinely. Other tests such as chlorine requirement and bacteriological quality were performed intermittently.

Because five-day BOD is a widely accepted parameter for sewage strength, this measure was used as the principal loading criterion. In order to establish acceptable organic loading values, 50 and 100 pounds of five-day BOD per acre per day were selected as loading rates for the first phase of the study.

Figures 3 and 4 show average monthly loading in terms of five-day BOD per acre per day. As the figures indicate, difficulty was encountered in maintaining those selected organic loading rates. Control was attempted by varying the pumping time, but the unpredictable change in waste strength made this control less than desirable. The varying organic loading rate was not considered to be a serious problem, however, because of the compositing effect

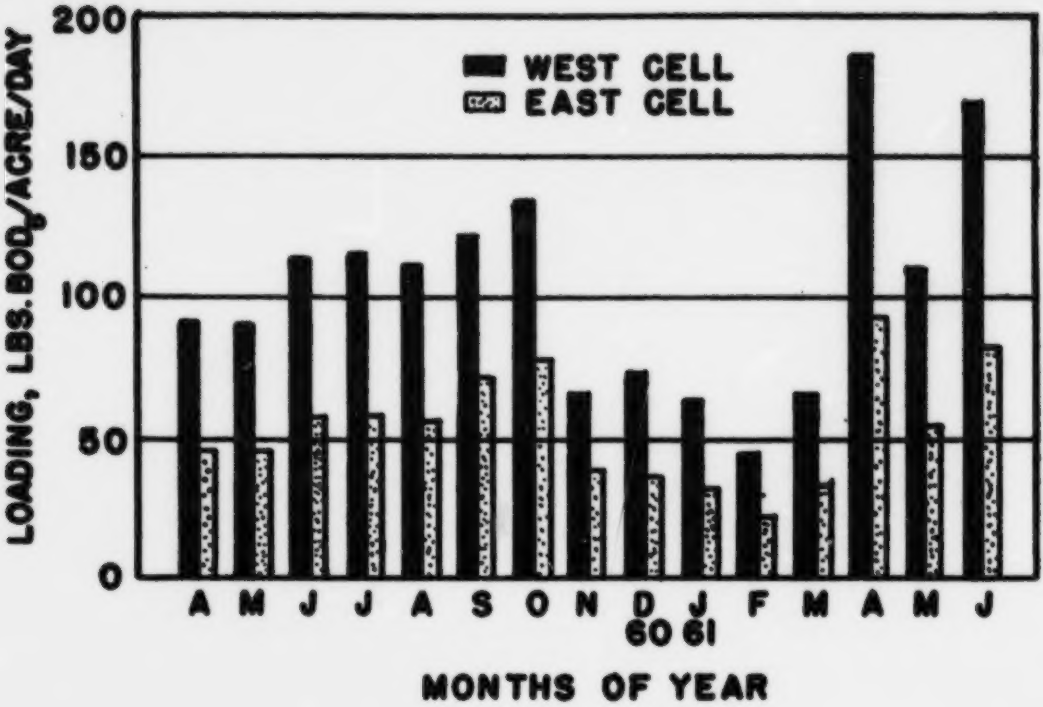


Figure 3. Average BOD Loading Rates, 1st Phase

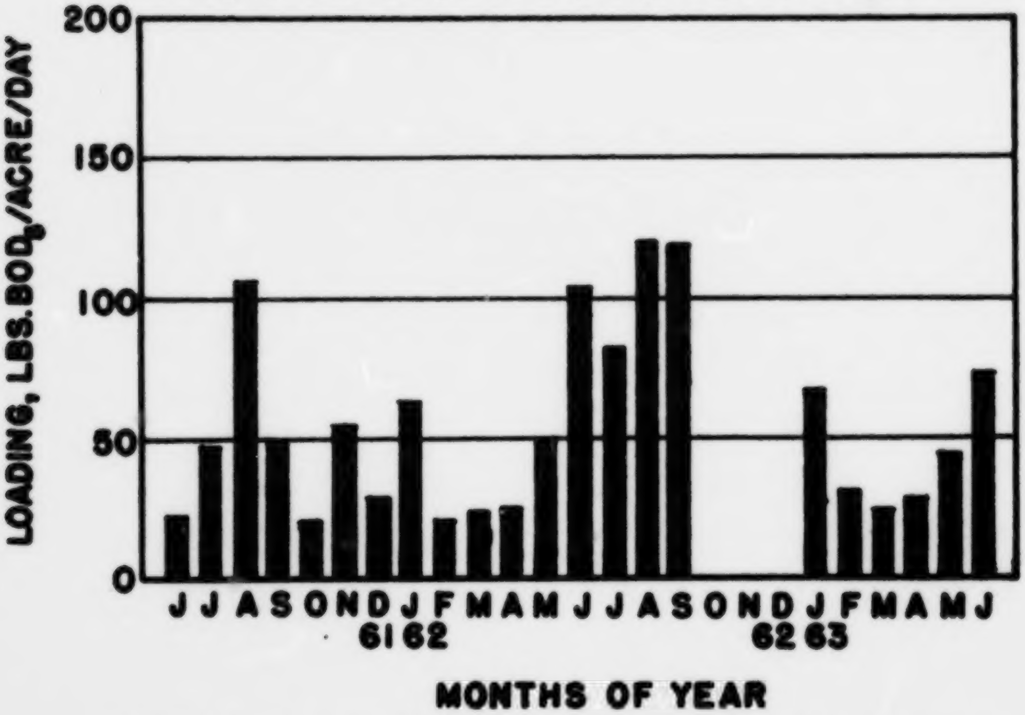


Figure 4. Average BOD Loading Rates, West Cell, 2nd Phase

of the lagoon. Detention time varied from a minimum of six days to about 25 days for the west cell, and from 12 to approximately 50 days in the east cell during the first phase of the study (See Table 1). For Phase II, detention times varied from 7 to 34 days.

Several failures to maintain aerobic conditions occurred during the course of the study. The first occurred in the west cell during the month of September, 1960. Typically, as failure occurred, the color turned to grey-green and highly objectionable odors were detected. A great deal of floating sludge was observed and a red ring of tubifex was visible at the water's edge. Tests performed on the effluent at this time indicated low to zero dissolved oxygen, low pH, high effluent BOD and low removal rates of BOD.

The BOD loading in the west cell, just prior to the September, 1960, failure, was approximately 120 pounds of five-day BOD per acre per day. In order to reestablish aerobic conditions, a period of recovery of 38 days was allowed. During this time, up until the failure just described, the east cell continued to operate satisfactorily without any visual evidence of failure condition, except for tubifex at the water's edge. Loading during this time was approximately 50 pounds of five-day BOD per acre per day. Increased activity in a local cannery operation caused more difficulty in controlling loading, with five-day BOD per acre per day as a loading criterion, than was previously experienced. For this reason loading in the east cell for the remainder of September varied from about 60 pounds of BOD per acre per day at the beginning down to 50, then up to over 90. The east cell, loaded at one-half these rates, continued to operate successfully with only tubifex as indication of failure or poor condition. Indicators of poor condition or failure were again observed several times during the course of the study. The conditions of poor color, floating sludge, tubifex visible at water's edge, and odor are compared in Figure 5 with the average organic loading for 30 days prior to occurrence of each condition.

Tubifex was first observed at 30 days average values of as low as 15 pounds of five-day BOD per acre per day. Floating sludge was observed at loading values of 24 pounds of five-day BOD per acre per day. Poor color condition which was associated with low algal activity and impending failure was observed at loading values as low as 24 pounds of five-day BOD per acre per day. Objectionable odors, which were used as an indicator of complete failure to maintain an aerobic condition, were observed at values of as low as 50 pounds of five-day BOD per acre per day.

During much of the time of the study, operation without any observable condition of impending failure was noted at organic loadings much higher than those listed in Figure 5, but during certain critical periods with increasing lagoon temperatures and the resulting increased decomposition rates, poor or failure condition was observed.

Suspended Solids (SS) determinations were routinely made during the first phase of the study and monthly averages in pounds of SS per acre per day are presented in Figure 6.

Suspended Solids (SS) determinations on the east (secondary) cell

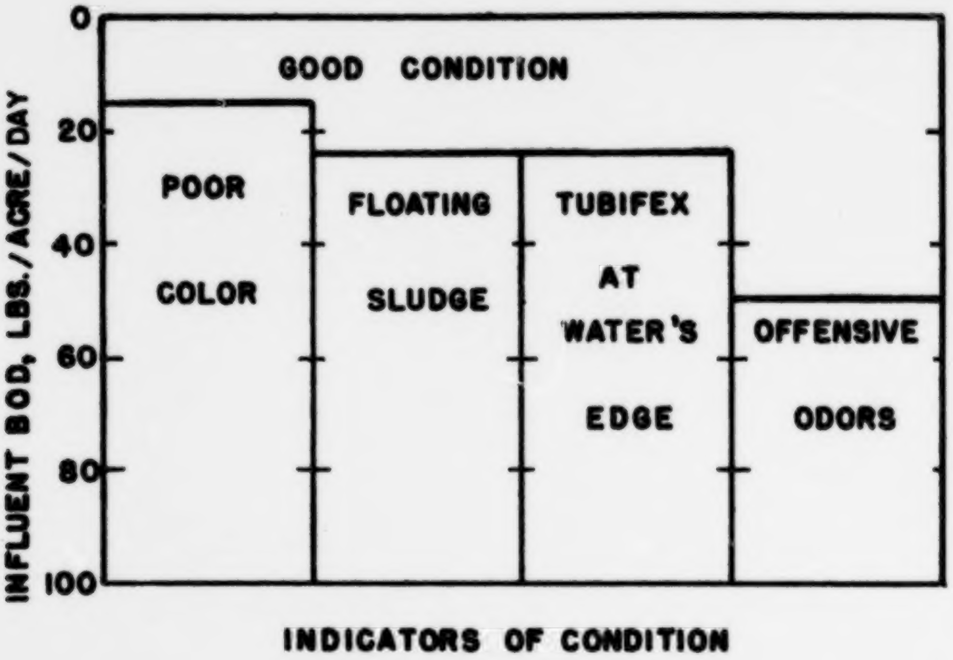


Figure 5. Threshold Loadings for Indicators of Poor Condition

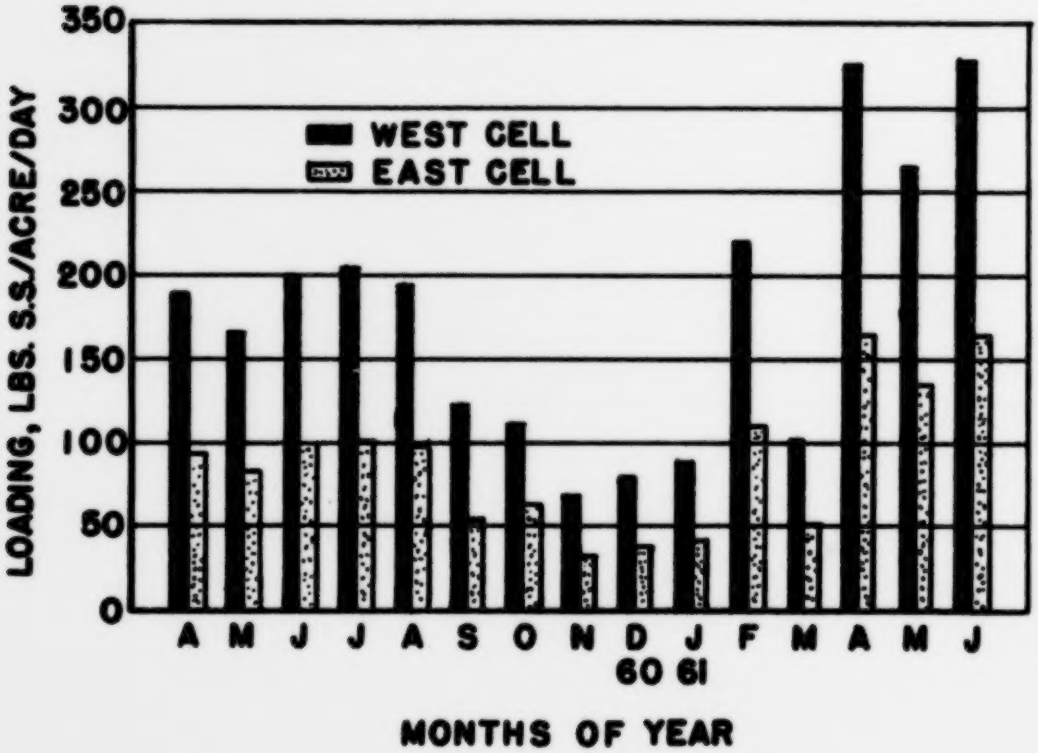


Figure 6. Average Suspended Solids Loading, 1st Phase

influent during the second phase of the study were not continued after preliminary determinations indicated that the significant part of SS was contributed by aquatic forms in the influent. SS determinations were not made on effluent for the same reason.

Detention Time

Since the expression of loading criteria for this study was pounds of five-day BOD per acre per day, flows and detention times were functions of influent BOD. Therefore, detention times varied with a continuously changing influent BOD. Average monthly detention times are listed in Table 1. Detention times during the failure and recovery periods are marked with an asterisk (*). These are not true monthly averages because loading during that time was discontinued to allow for a period of recovery.

Quality of Effluent

Tests for an indication of the quality of effluent from the two cells of the lagoon used in this study included dissolved oxygen (DO), pH, BOD, transmittance of light, coliform density and chlorine requirement.

Dissolved Oxygen

Results of dissolved oxygen determinations for the first phase (cells in parallel) are presented as monthly averages in Figure 7. DO concentration varied from supersaturation during early spring and summer periods to zero at the point of failure. Averages shown for the first phase were from measurements taken at approximately 2 p.m. daily. Since DO concentration is maximum in mid-afternoon, the slope of the diurnal variation of DO curve

Table 1. Volumetric Loading

Phase I. Parallel Loading

	West cell		East cell	
	Detention days	Days loaded	Detention days	Days loaded
April	18.6	26	37.2	26
May	18.6	31	37.2	31
June	18.6	30	37.2	30
July	20.2	31	40.5	31
August	21.2	31	42.0	31
September	130.0*	6	43.9	30
October	64.0*	17	43.9	31
November	103.0*	7	50.0	30
December	23.2	31	46.6	31
January	19.8	31	39.6	31
February	10.9*	24	21.8*	24
March	6.0	31	12.0	31
April	7.4	30	14.8	30
May	11.4	31	22.8	31
June 1-13	11.8	13	23.6	13

Phase II. Series Loading

	Combined		West cell	East cell
	Detention days	Days loaded	Detention days	Detention days
June 14-30	41.0	17	20.5	20.5
July	31.2	31	15.6	15.6
August	21.0	31	10.5	10.5
September	60.6*	27	30.3	30.3
October	64.0	31	32.0	32.0
November	27.0	30	13.5	13.5
December	22.6	31	11.3	11.3
January	25.0*	27	12.5	12.5
February	18.7	28	9.4	9.4
March	21.9	31	10.9	10.9
April	23.4	30	11.7	11.7
May	16.8	31	8.4	8.4
June	14.8	30	7.4	7.4
July	16.0	31	8.0	8.0
August	71.0*	24	35.5	35.5
September	78.2*	26	39.1	39.1
January	31.6	31	15.8	15.8
February	32.8	28	16.4	16.4
March	34.0	31	17.0	17.0
April	34.4	30	17.2	17.2
May	30.0	31	15.0	15.0
June	23.2	30	11.6	11.6

* Loading not continuous

(See Figure 20, page 47) approaches zero. Two p.m. was chosen as the most probable time in a winter-summer operation for this maximum condition to occur

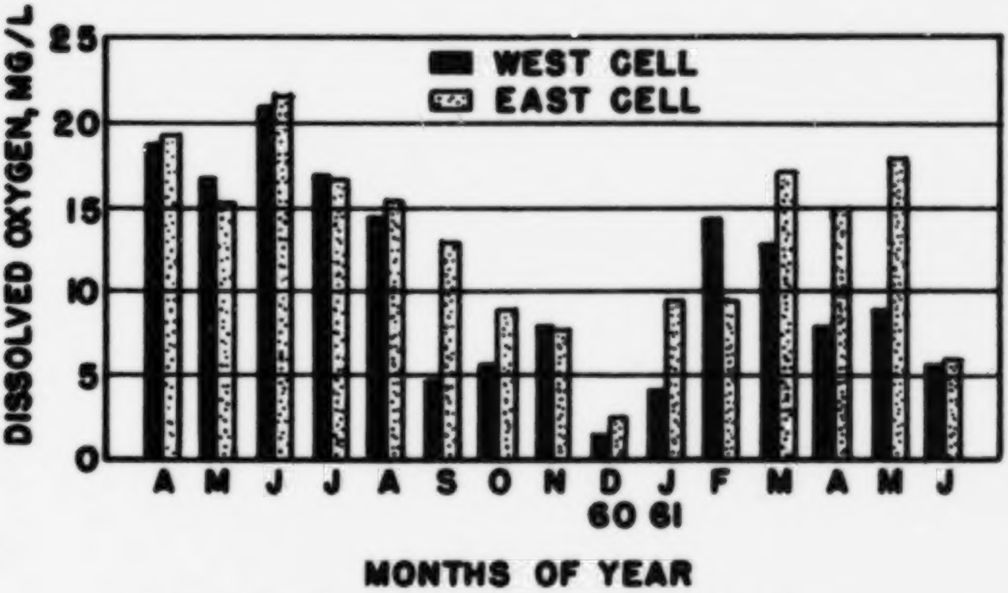


Figure 7. Dissolved Oxygen Averages, 1st Phase

The results of dissolved oxygen determinations for Phase II (cells in series) of the study are presented in Figure 8. A true comparison of the DO values (first and second phase) for corresponding summer months cannot be made without considering diurnal fluctuation (See Figure 20, page 47). During the second phase it was necessary to change the sampling point to a point near the lagoon where no refrigeration was available. To minimize the effect of decomposition during the time of sample compositing, loading was changed to early morning and loading samples were picked up at approximately 9 a.m. Although oxygen concentration changed during the day to the extent that

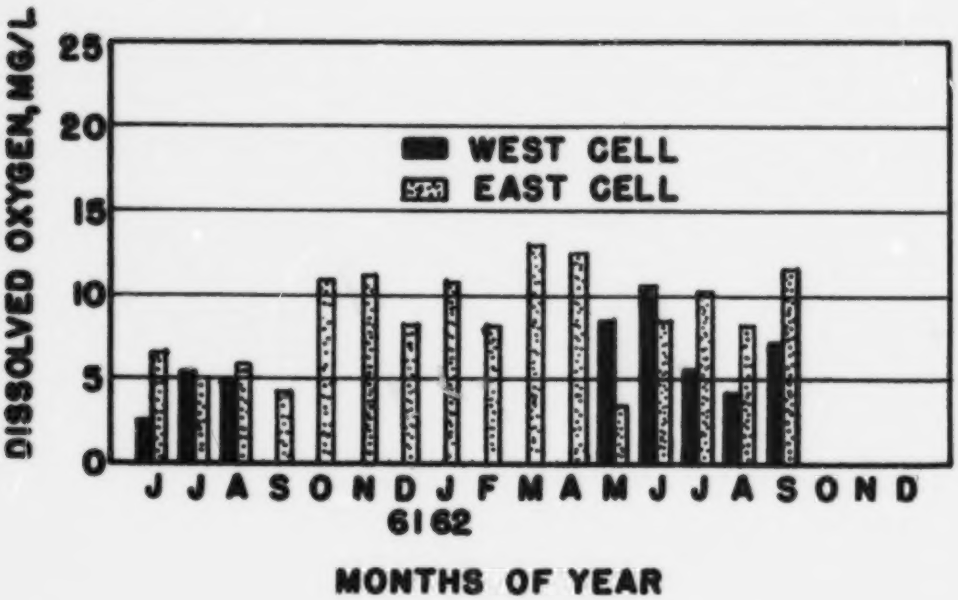


Figure 8. Dissolved Oxygen Averages - 2nd Phase

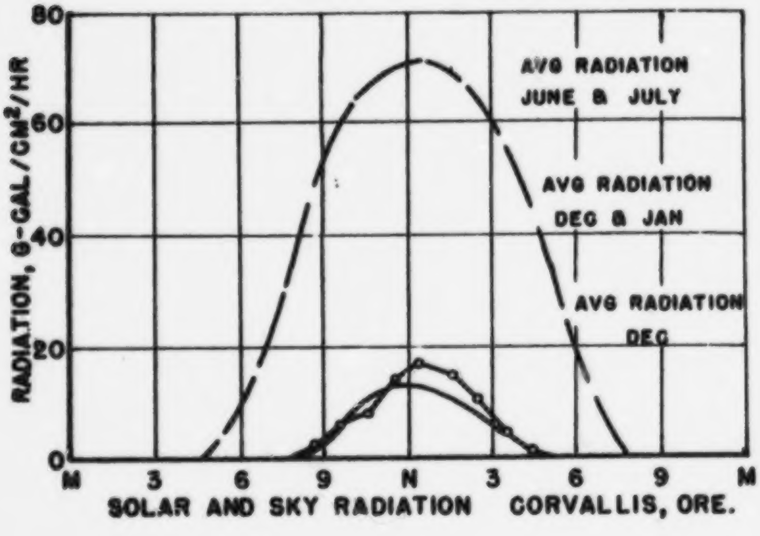


Figure 9. Diurnal Variation in Solar Radiation

comparison of DO in parallel and series operation was difficult, this was considered no great disadvantage when diurnal variation of DO is considered.

Included in the dissolved oxygen (DO) averages of the west cell for the months of September, October, and November, 1960, are DO values taken during the period of recovery when no load was applied to the cell. This would account for the high DO concentrations during and immediately following times when failure occurred.

A sampling depth of 6 inches below the surface and at the point of outlet to the receiving stream in each cell was used for routine measurements. The unmodified Winkler method was employed in determining DO values, and it was recognized that interfering elements and compounds were probably present in these samples being tested. For this reason, results are not precise, but are only indicative of the DO level of the cells at the time of sampling. Dissolved oxygen values shown in Figures 7 and 8 are merely one determination indicating general conditions in a continuously changing situation. These data are, therefore, qualitative rather than quantitative.

pH

pH was determined for the effluent discharge from the two cells of the lagoon. The monthly median of pH and the pH range for each cell are listed in Table 2. Low pH values were noted at times of poor lagoon condition.

Table 2. pH Data Summary

	West Cell		East Cell	
	Median	Range	Median	Range
*April, 1960	8.8	7.0-10.4	9.0	7.3-10.8
May	9.2	8.5-10.6	9.2	8.3-10.6
June	9.5	8.0-11.0	9.9	8.5-10.8
July	9.1	8.3-10.4	9.3	8.2-10.7
August	9.3	7.0-10.0	9.7	8.3-10.7
September	7.3	7.0- 9.5	7.2	7.0-10.2
October	7.3	6.6- 9.4	8.7	7.1-10.2
November	7.1	7.1- 8.6	7.5	7.2- 8.5
December	6.8	6.5- 7.1	7.0	6.9- 7.4
January, 1961	7.1	6.2- 7.4	7.2	6.2- 8.4
February	7.3	6.9- 8.6	7.3	7.0- 8.1
March	7.6	7.6- 9.1	8.3	8.0- 9.2
April	7.4	7.3- 8.8	8.7	7.7- 9.3
May	7.5	7.4- 8.5	8.8	8.5- 9.5
June		7.4- 8.4		8.8- 8.9
**June	7.8	7.6- 7.8	8.6	8.4- 9.2
July	8.7	8.2- 9.3	8.8	8.7-10.0
August	8.8	7.6- 9.0	9.0	8.8- 9.7
September			7.2	7.2- 7.6
October			8.9	7.9- 9.5
November			8.3	7.3- 9.0
December			7.3	
January, 1962			8.3	7.7- 8.8
February			7.4	7.2- 8.1
March			8.4	7.2- 8.4
April			8.3	7.4-10.4
May	7.8	7.2- 8.7	7.2	7.1- 9.0
June	8.3	7.4- 9.2	8.5	7.3- 9.3
July	7.5	6.6- 8.4	7.5	7.3- 9.0
August	7.2	6.7- 8.0	8.8	8.3- 9.3

* Phase I Parallel operation

** Phase II Series operation

BOD Removal

The quality of effluent in terms of BOD removed is partially presented in the form of monthly averages (See Figure 10). These efficiencies were calculated from five-day, 20-degree BOD data for the raw influent and for the effluent with no additional treatment as it was discharged to the receiving stream. Efficiencies calculated on this basis for a single cell indicated a degree of removal up to and above 80 per cent during the periods of aerobic operation.

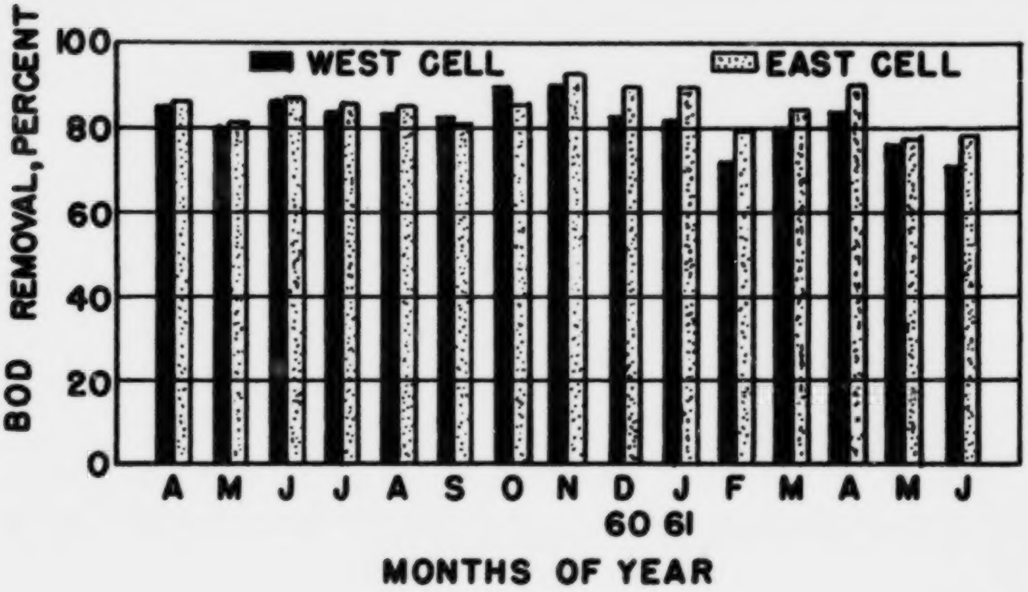


Figure 10. Monthly Averages of Apparent BOD Removals - 1st Phase

Efficiency values for the east cell, when operated as a secondary cell in series, were much lower than those shown for primary operation with removals ranging from a high of 50 per cent to a low of about 20 per cent of that BOD applied to the secondary cell.

During the periods just prior to failure, average efficiencies in the primary cell dropped to as low as 23 per cent. A partial, but typical, sample of these data is shown in Figure 11. BOD removal efficiencies at failure could not be calculated because loading was discontinued at that time to allow for a recovery period.

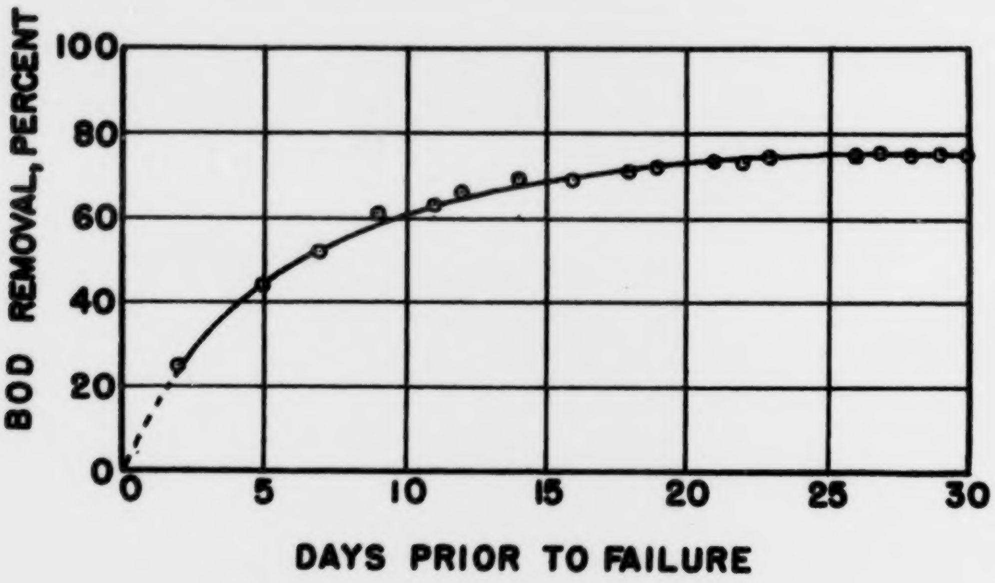


Figure 11. Accumulative Averages of Percent Removal Prior to Failure

The conventional BOD test, measuring total oxygen respiration in the sample bottle during incubation, may have an unknown bearing on the pollutional nature of lagoon effluent since much of the material is in the form of living cells that would not affect the receiving stream in the same manner it affects BOD measurement. The rather basic question of interpreting results remains. Is the organic loading of a waste reduced when treated in aerobic lagoons or is the organic loading merely transformed into living cells? The nature or form of the material causing BOD becomes critical particularly in those cases where disinfection is required. Determination of BOD to include the algal cells was performed on heat killed and seeded samples. Both filtered and unfiltered samples were tested. An inspection of the data presented in Figure 12 shows the increase, percentage wise, of BOD by heat killing the unfiltered samples.

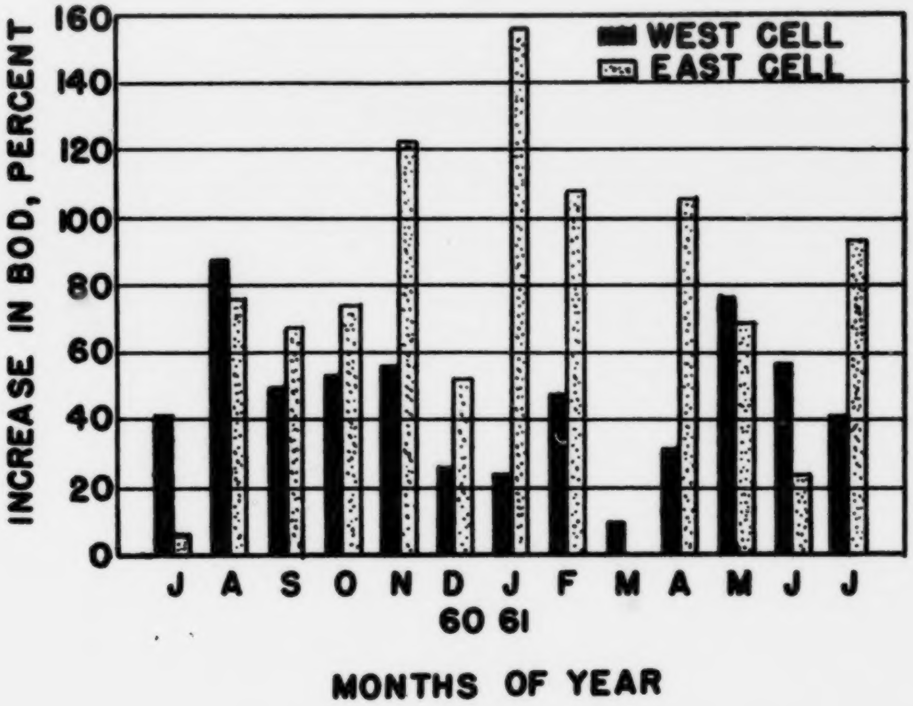


Figure 12. Average Percent Increase of BOD by Heat Treating Effluent

It is felt that heat killed unfiltered samples represent more nearly the true BOD load placed on the receiving stream when disinfection of the effluent is practiced. In most cases the BOD for the heat killed unfiltered samples was higher than that of the untreated samples. In some instances the total load of BOD leaving an oxidation lagoon may be higher than that in the incoming raw sewage if disinfection is practiced on the effluent stream. This factor is discussed further in a later section of this report.

Light Transmittancy

Transmittancy determinations were made on samples of the influent and effluent for comparison purposes. These samples were placed in a centrifuger to separate the supernatant and the residue. Transmittancy determinations were made on the supernatant using a Beckman spectrophotometer at a wave length of 650 microns.

Values determined for transmittancy ranged from approximately 70 to 95 per cent for both the effluent from the two cells and for the influent. The lowest values were recorded at a time when an anaerobic condition existed. As a general rule, transmittancy decreased as conditions deteriorated. No particular correlation was evident through comparison with other parameters, however.

Bacteriological Quality

Bacteriological quality of the lagoon effluent is of particular importance in a maritime region. Since annual precipitation exceeds annual evaporation, the resulting lagoon effluent must be disposed of by dilution within an existing water course or handled in some other satisfactory manner. In many cases, the receiving stream may be used for many other purposes such as irrigation, recreation and fishlife, and as a source of domestic water supply.

In all cases the bacteriological quality must be considered. This quality is quite variable, and is not only affected by bacterial species, lagoon environment, and waste water quality, but also by the relationship of the location of the lagoon inlet to the outlet, wind direction, lagoon short-circuiting, and rate of hydraulic loading or detention time. As may be expected, the bacteriological quality of the lagoon effluent varies from day to day and within the time of any one day.

Bacteriological studies for Phase I of the study were limited to samples collected on selected days at approximately 10 a.m. These were analyzed for coliform density by the Millipore filter technique. Techniques employed were those listed *Standard Methods for the Examination of Water, Sewage and Industrial Wastes*, 11th ed., American Public Health Association, *et al.*, at the suggestion of Mr. H. F. Clark, microbiologist with the U. S. Public Health Service at the Robert A. Taft Sanitary Engineering Center in Cincinnati, Ohio (now deceased).

Results of bacteriological studies in terms of coliform reduction are shown in Table 3. In most cases coliform organism concentrations were significantly less in the lagoon effluent than in the influent. However, short circuiting of the cells due to wind currents caused some variation of this pattern. This suggested a laboratory experiment for series lagoons that is discussed in the section on "Receiving Stream Studies" that appears later in this report.

Table 3. Bacteriological Results

Col. Bact. per ml/100*

	Raw		West cell		East cell		Ave. % Red.	
Date	Hi	Low	Hi	Low	Hi	Low	West	East
August, 1960	1800	25.0	60.00	10.20	79.0	4.20	80.0	91.6
September	440	110,0	6.50	1,70	80,0	9.00	98.7	89.2
December	770	50,0	14.00	2.40	0,6	0,45	96.7	99.5
January, 1961	30	25.0	22.00	0,15	3.2	0,15	72.7	93.6
April	50	3.0	0,60	0.50	0.2	0,01	92.8	99.5
May	15	2.3	0,44	0,08	0.4	0.05	96.9	97.7
**								
June	7300	350.0	15.00	13.00	7.5	3.00	98.1	61.1
July	3800	130,0	280,00	25.00	31,0	3.00	80.7	53.3
August	7000	80,0	70,00	0,90	15,0	1,00	95.0	80.6

* Coliform/ml = reported figure X 100
Coliform/100 ml = reported figure X 10,000
** Series loading West to East cell

Disinfectant Requirement

Even with the large reduction of coliform organisms shown in Table 3, the bacteriological quality of the effluent indicates that, based on current standards, disinfection is advisable under certain circumstances. Merits of disinfection and the problems of after growth are recognized, but since these are the subject of current studies by other investigators, no attempt has been made to interpret disinfection in this report.

A widely accepted criteria for chlorine requirement is stated as that dosage of chlorine which will provide a residual of 0.5 mg/L after a contact time of 30 minutes. This criteria was used as a basis for determining chlorine requirement. It was accomplished by dosing samples with various amounts of chlorine so as to bracket the requirement values. The residual in each sample was determined by the orthotolodine test. Table 4 is a listing of data so

Table 4. Disinfection Requirements

	Cl_2 requirement mg/L to 0.5 mg/L residual		
Date	Raw influent	West effluent	East effluent
*1960			
8- 1	6.0	6.0	6.0
8- 8	5.0	6.0	9.0
8-15	10.0	6.0	6.0
8-19	4.0	5.0	8.0
8-22	7.5	7.0	7.5
8-29	-	13.5	13.5
8-31	13.0	10.5	16.0
9- 5	6.0	6.0	12.0
9-12	-	6.0	8.4
9-19	9.0	3.0	9.0
10-28	2.0	3.0	3.0
12-19	2.0	4.0	2.0
12-24	5.0	2.8	2.0
1961			
1- 7	3.0	2.0	2.0
1-14	3.0	2.0	2.0
2-14	7.0	2.5	2.0
3- 4	-	3.0	2.0
3-11	2.0	1.5	1.5
3-18	1.0	1.0	2.0
3-25	1.4	2.0	3.5
4- 1	2.0	1.5	2.5
4- 8	2.5	2.5	2.5
4-15	2.0	2.0	2.5
4-22	3.5	5.0	5.0
4-29	2.5	2.5	3.0
5- 6	2.5	3.0	2.5
5-13	2.0	3.0	2.5
** 6-14	16.0	4.0	4.0
6-21	1.4	2.5	2.4
6-28	2.5	3.0	3.5
7- 5	4.0	4.5	4.0
7-12	3.0	7.0	8.0
7-19	4.5	3.0	12.0
7-26	2.5	6.0	7.0
8- 2	5	9	7
8- 9	4	3	10
8-16	3	3	6
8-23	7	4	4

* Phase I Parallel operation

** Phase II Series operation

determined.

It is of interest to note that during late August, 1960, and July, 1961, an unusually large chlorine requirement was coincident with unsatisfactory lagoon conditions. It should also be noted that the chlorine requirement of the effluent was at times greater than that for raw sewage. An indicated earlier in a discussion of heat treated effluent, algae killed, coincident to chlorination, contribute a significant source of dead and readily decomposable organic matter to effluent stream. In many cases, the quality of effluent from a BOD standpoint may be equivalent to raw sewage. This factor indicates that either closely controlled chlorination to affect desired disinfection without effecting lagoon operation, or removal of algae prior to effluent chlorination could be required when disinfection is necessary.

Bottom Sludge

Decomposition of bottom deposits and the oxygen used in this process makes sludge accumulation and distribution an important consideration in oxidation lagoon criteria. Since the sludge blanket is in a constant state of change, single samples from one location have little individual significance and over-all conditions must be measured. A program of determining change in sludge depth, composition and distribution was undertaken in the lagoon study. Core samples were collected in plastic sample tubes, 1.25 inches in diameter, from permanent sampling stations. These were analyzed for sludge composition and depth. Table 5 is a partial tabulation of the data available from these tests. Figure 13, showing typical sludge samples, illustrates the sampling tubes and sludge variation at the several sampling points and for the dates listed. Sample numbers are referenced to stations shown in Figure 1, and to sample identification (i.e., sample L10, B3W is sample number L10 at location B3W).

Table 5. Sludge Accumulation

West cell				East cell			
Location	Depth ft	lb/ft^2	% vol.	Location	Depth ft	lb/ft^2	% vol.
Data from samples taken March 21, 1961							
W1	0.61	3.90	32	E1	0.72	3.82	54
W2	0.57	2.89	33	E2	0.55	1.95	41
W3	0.42	1.69	32	E3	0.30	1.08	35
B4W	0.39	1.67	30	B4E	0.33	1.42	37
B2W	0.23	1.07	31	B2E	0.15	1.56	22
W4	0.30	1.38	28	E4	0.25	0.89	35
W5	0.23	1.07	29	E5	0.27	1.31	33
B3W	0.25	1.03	28	B3E	0.22	0.92	32
W6	0.22	0.76	29	E6	0.26	1.88	22
B1W	0.35	1.90	25	B1E	0.26	2.02	22
W0F	0.16	1.70	13	E0F	0.24	3.56	10
Data from samples taken March 10, 1962							
W1	0.34	5.17	11.7	E1	0.24	5.0743	16.9
W2	0.23	1.10	47.5	E2	0.24	1.14	29.6
W3	0.23	1.50	37.0	E3	0.24	0.94	28.6
B4W	0.24	0.66	26.7	B4E	0.20	1.05	24.4
B2W	0.13	1.44	29.9	B2E	0.16	0.26	34.3
W4	0.20	0.80	32.5	E4	0.18	1.25	46.1
W5	0.15	0.60	27.6	E5	0.14	0.63	27.1
B3W	0.14	0.63	26.3	B3E	0.19	0.51	33.4
W6	0.18	0.87	22.1	E6	0.15	0.61	37.0
B1W	0.18	0.68	26.3	B1E	0.15	1.40	30.0
W0F	0.18	1.44	19.5	E0F	0.17	0.50	24.4

lb/ft^2 = pounds of sludge per sq ft of bottom
percent fixed = 100 - percent volatile

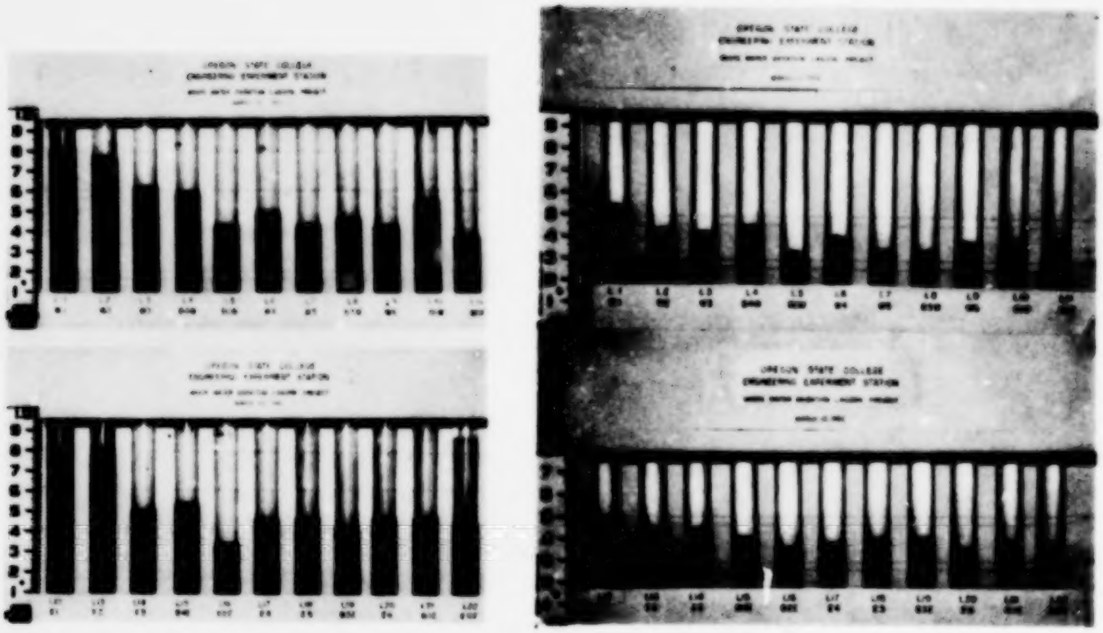


Figure 13. Bottom Sludge Samples

Draining of the lagoon at the end of the study revealed sludge deposits at the end of each influent pipe approximately 30 feet wide and extending approximately 80 feet from the end of the pipe (See Figure 14) and in the direction of flow. The greatest depth of sludge upon drying appeared to be about four to five inches thick, but no true line between sludge and bottom soil was determinable. Whether mixing of soil and sludge resulted from bottom currents or from the action of bottom biota is unknown. This soil-sludge mixture did, however, make determination of decomposable material impractical.

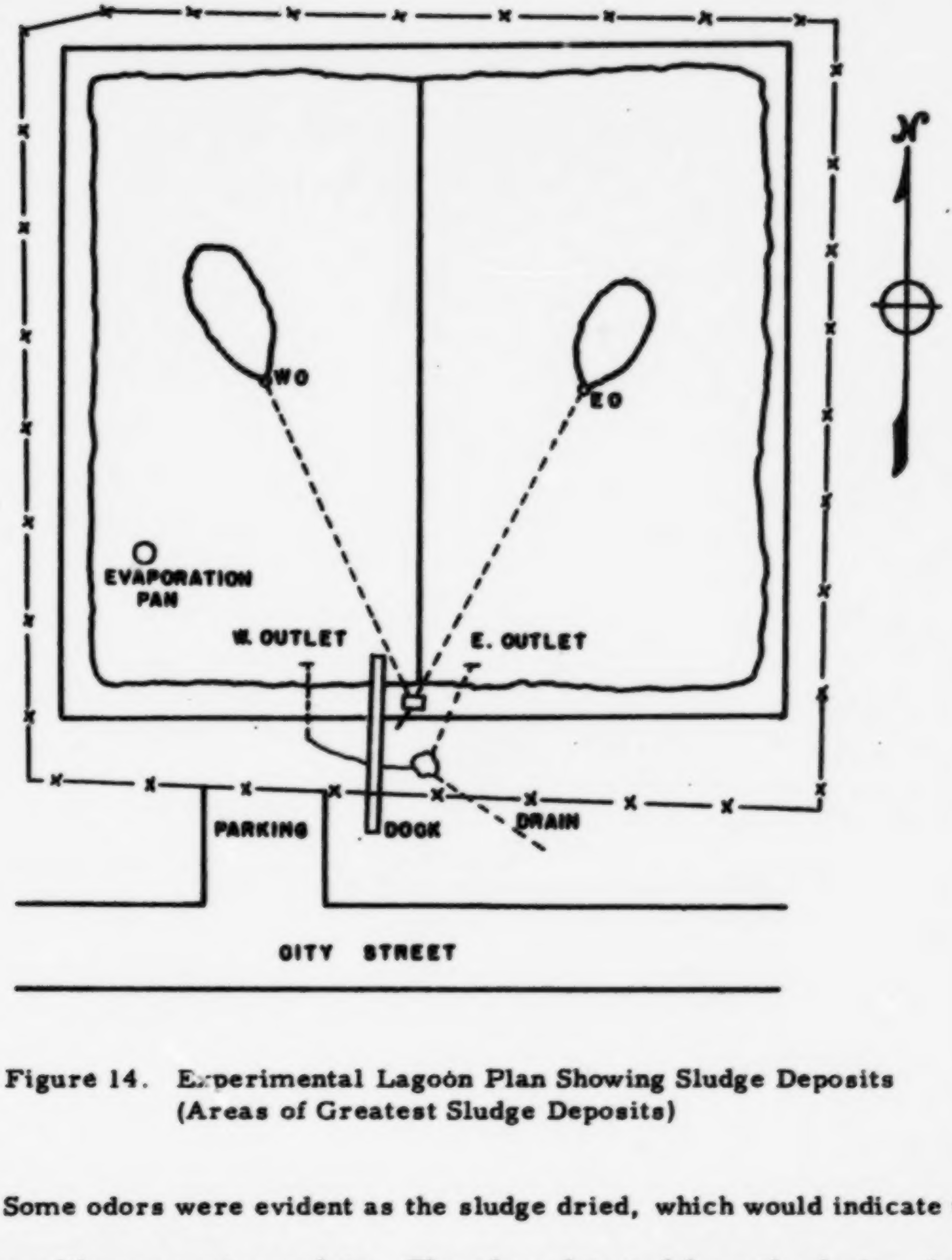

WO
EO
EVAPORATION PAN
W. OUTLET
E. OUTLET
PARKING
DOCK
DRAIN
CITY STREET
N

Figure 14. Experimental Lagoon Plan Showing Sludge Deposits (Areas of Greatest Sludge Deposits)

Some odors were evident as the sludge dried, which would indicate that decomposition was not complete. The odors detected from the drying sludge were not those associated with an anaerobic condition, but were similar to those odors detected when floating sludge was observed. The significance of sludge deposits was studied separately by Graduate student Mr. G. L. O'Neal. These studies were not completed during the grant period. Preliminary analysis, which provides some insight as to sludge significance, is presented in Appendix C.

Public Health Aspects

Several public health aspects other than that associated with effluent and down stream use of water must be considered.

Ground Water Contamination and Soil Sealing

One requirement for successful lagoon operation is "water tightness" or impermeability of the lagoon bottom and levees. A seepage rate of 1/4 inch per day from a one acre lagoon would equal that daily waste water from a population of 68 persons at a daily per capita production of 100 gallons. Excessive seepage in installations located in the Midwest prevented optimum operating depths from being obtained (12). Figure 15 is a photo of one of several lagoons constructed in Oregon where optimum operating levels have never been maintained.

Where seepage occurs, ground water contamination is a cause for concern. However, lagoons should be constructed to hold water. Compaction after scarifying to a depth of six inches of natural soils is often sufficient. Artificial sealing with coalescing chemicals, clay, plastic membranes or asphalt application may be necessary in some cases and should be used if local conditions so dictate.

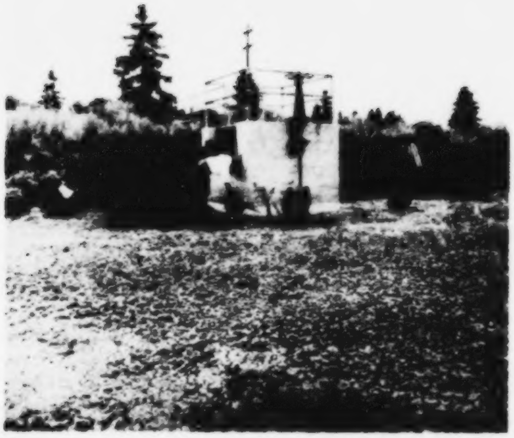


Figure 15. Photograph of Lagoon and Outfall Structure Where Minimum Water Level was Never Maintained

Efforts were made to study rates of percolation and soil sealing capabilities of sewage in an effort to determine suitable soils for lagoon construction. Permeameters with several types of soil ranging from sand and gravel to loams and clays were placed below the lagoon surface under a head of three feet. Results from this effort were inconsistent and much less than expected. Conclusions reached as a result of this effort were that seepage will occur in the more permeable materials. There is a tendency for soil to be sealed as time passes. In some cases, with the more permeable materials, sealing is affected by a simple mechanical plugging by the solids load in the sewage. In other cases, especially in some of the clay materials, sealing results not only from impermeability of soil, but also from chemical changes within soil particles exposed to the waste water.

Mosquito Control

The statement that lagoons provide a place for mosquito breeding *cannot be denied*. The question as to whether lagoon-bred mosquitoes are a hazard to public health *has been and continues to be raised*.

There is some evidence that mosquitoes emerging from highly polluted sources in this area do not bit man (19). Lagoon bred mosquitoes do constitute a possible hazard (5) and at the very least a nuisance; therefore, provision should be made to control them. In the experimental lagoon efforts to accomplish mosquito control were made by control of aquatic weeds which eliminated a harborage for larvae and by planting the small fish *Gambusia affinis* that has been proven effective in controlling mosquitoes in many areas.

A three-foot water level in the lagoon was maintained to control aquatic weeds. Marginal weeds close at the water's edge were controlled by mowing and spraying with a herbicide. This eliminated much of the problem, but mosquito larvae were still observed at lagoon edges. *Gambusia* were then introduced as a possible method for mosquito control. They were planted in control vessels and in the lagoon. Soon after planting, control vessels were larvae free, however, no change in the numbers of larvae in the lagoon was evident. Complaints from home owners living close by made larvicide spraying of the lagoon and control vessels necessary. The *Gambusia* in the control vessels failed to survive the spray. Whether the *Gambusia* planted in the lagoon were killed by spray or whether the pollutional or high organic load was too great is not known with certainty. Carp and other trash fish planted in the lagoon failed to survive after planting. It can be concluded that weed control and larvae spraying offer a practical method of mosquito control in lagoons.

Controlled Access

Protection from direct contact with contaminated water in lagoons is important. Therefore, signs on well constructed fences to warn the public as to the lagoon contents are necessary. Fencing should be so constructed that access is not possible for children, pets or domestic animals.

Water fowl, including ducks, geese and, for a period of time, a swan, were observed on the Oregon State University experimental lagoon.

The possibility of disease transmission by water fowl carrying contamination from lagoons to open reservoirs constitutes a definite hazard and the advisability of allowing accessibility of water fowl and wild animals to lagoon areas has been question for concern (13).

Aesthetic Factors

Color, Odor and General Appearance

During the period from April to September, 1960, the color of both cells was dark green and no offensive odors were detectable. This appearance was associated with high algal activity and an aerobic condition. In early September, 1960, the west cell began changing from a green to a gray color. Algal counts dropped proportionately, and a red ring of tubifex was observed around the edges of the west cell. The change in aquatic life was punctuated by very objectionable odors and floating sludge, associated with an anaerobic condition. Loading of the west cell was discontinued to permit re-establishment of satisfactory aerobic conditions.

A recovery period of about five days was permitted, during which objectionable odors diminished, algal activity increased, and the tubifex disappeared. Loading greater than could be tolerated in the west cell was started before a complete recovery, however, because the failure cycle was experienced twice more in the following months. Through the winter months algal activity in the east cell was low and the color turned gray, but no floating sludge or tubifex were observed nor were objectionable odors detected.

In 1961, during the months of April, May, and the first week of June, the condition of each cell was aerobic. Color of both cells was dark green and no tubifex ring or objectionable odor was evident. Starting with the second week of June, the color in the west cell changed to a slight brownish-green, while the east cell remained a deep green color. Vigorous gas production was noted in both cells, but little or no odor was detected. As a result of the gas production, sludge floated to the top and covered approximately 15 per cent of the surface area of the west cell (See Figure 16). No sludge was observed on the east cell.

The absence of any wind, which would break up sludge blankets and allow the solids to settle, and the presence of warm, dry weather caused the sludge to dry on the surface where it remained for approximately three weeks.

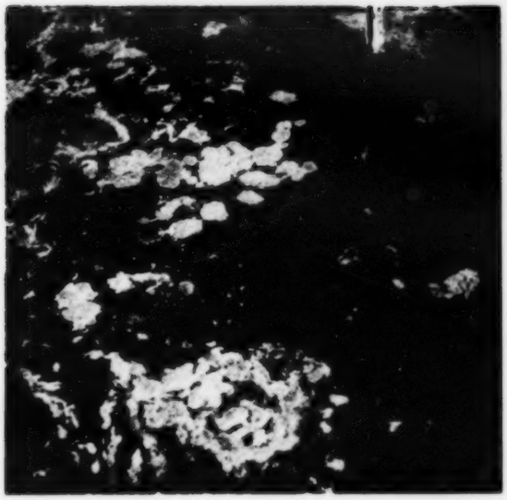


Figure 16. Floating Sludge

A slight odor was detected issuing from the floating sludge, but other than the color change and floating sludge on the west cell no observation or test result of the effluent indicated anything but an aerobic condition. Though odors were detected, of greater nuisance was the fact that the floating sludge blanket provided an excellent place for fly and mosquito larvae to hatch.

A rain shower, accompanied by a brisk wind, occurred about three weeks after the floating sludge first appeared causing the sludge to break up and settle.

The east cell, loaded at one-half the rate of the west cell, approximately 50 pounds of five-day BOD per acre per day, operated satisfactorily throughout the first phase or the initial test period. It was believed the critical loading values were bracketed in the initial test.

Foaming

Foam caused by detergents was observed at the outlets of the cells of the lagoon and Figure 17 shows this condition on a typical day. The free fall of the outlet provided sufficient turbulence to cause foam. Detergent survival through the lagoon process was not a subject of study during this lagoon project.

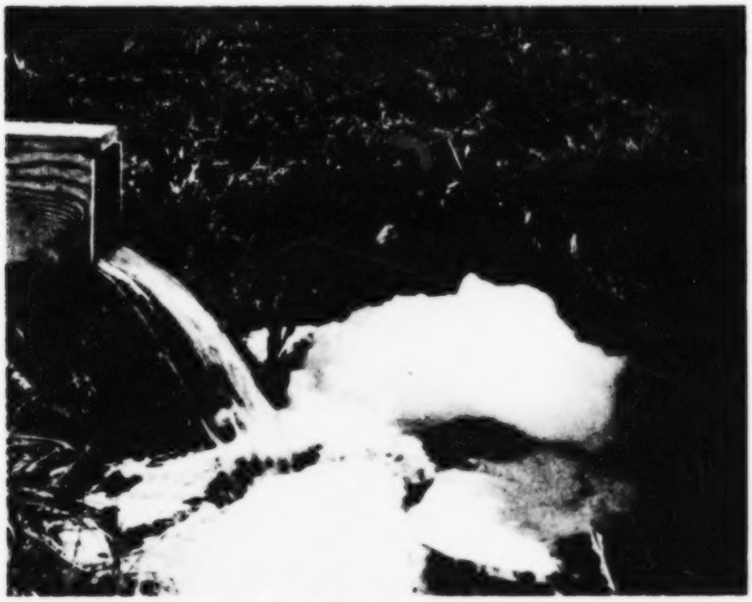


Figure 17. Foaming at Outlets

IV. RELATED LAGOON CHARACTERISTICS

Climatological Measurements

The phtosynthetic process of algal forms is dependent not only on solar energy but on products of bacterial decomposition. But since the bacterial decomposition rate is a function of temperature and since temperature is a function of solar energy, it follows that the successful operation of an aerobic lagoon for treating waste water organics is solar energy dependent (21).

Since lagoon performance is closely related to climatological conditions, rather complete weather data were obtained. Data on temperature and precipitation were obtained from Oregon State University Farm Crops Department weather station. Solar energy measurements were made with an Eppley pyrheliometer, equipped for continuous recording, located 3 miles southeast of the experimental lagoon. Results of the solar energy measurement were recorded in terms of gram-calories per square centimeter. (A gram-calorie per square centimeter per day is equivalent to 1 Langley/day.)

Net precipitation-evaporation measurements were made in a silver-colored evaporation pan 4 feet in diameter and 3.5 feet deep, sunk in the lagoon and equipped with a Stevens hook gage for determining net water level changes. No significant temperature differences were found to exist between the water in the evaporation pan and the lagoon water. A summary of climatological data for the Corvallis area in terms of monthly averages is shown in Table 6.

Table 6. Weather Data Summary

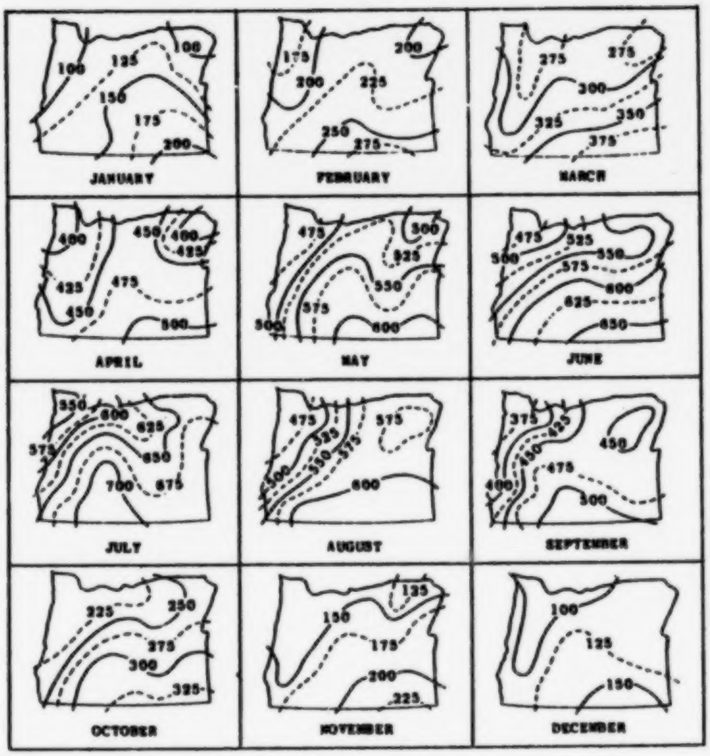
	Air temperature, °F**			Precip**	Solar energy*	Evap**
	Max	Min	Mean	in.	gm cal/cm^2/day	in.
January	45.3	32.5	39.0	6.42	109	-
February	50.5	35.1	42.8	5.10	132	-
March	55.3	37.0	46.2	4.06	164	-
April	62.3	40.5	51.4	2.10	395	2.55
May	68.8	44.9	56.9	1.85	454	4.05
June	73.4	49.3	61.4	1.29	685	4.64
July	81.3	51.9	66.7	0.32	697	4.35
August	80.9	51.4	66.2	0.38	524	6.00
September	76.8	48.8	62.8	1.30	406	3.94
October	64.7	43.4	54.3	3.53	234	2.05
November	53.1	37.5	45.4	5.44	128	-
December	48.1	35.7	41.7	6.15	91	-

* Data available.

** Approx 25-year average.

Under natural conditions the photosynthetic process is dependent on solar radiation. Figure 9 (page 21) shows typical diurnal variations throughout the day expressed as an average for summer and winter months.

Information concerning solar radiation for Oregon on a state-wide basis was not possible because only a very few pyrheliometer stations are in operation. What data that were available, however, were compiled by Gilbert Sternes of the U.S. Weather Bureau in the form of iso-radiation and percent of sunshine maps. This data appears in Figures 18 and 19.


JANUARY
100
125
100
150
175
200
FEBRUARY
175
200
200
225
250
275
MARCH
275
275
300
325
350
375
APRIL
400
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MAY
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JUNE
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JULY
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575
650
700
675
AUGUST
475
575
525
550
575
500
600
SEPTEMBER
375
425
450
450
475
400
500
OCTOBER
225
250
275
300
325
NOVEMBER
135
150
175
200
225
DECEMBER
100
125
150

Figure 18. Average Monthly Solar Radiation Data for Oregon (Langleys/day) (After Sternes)

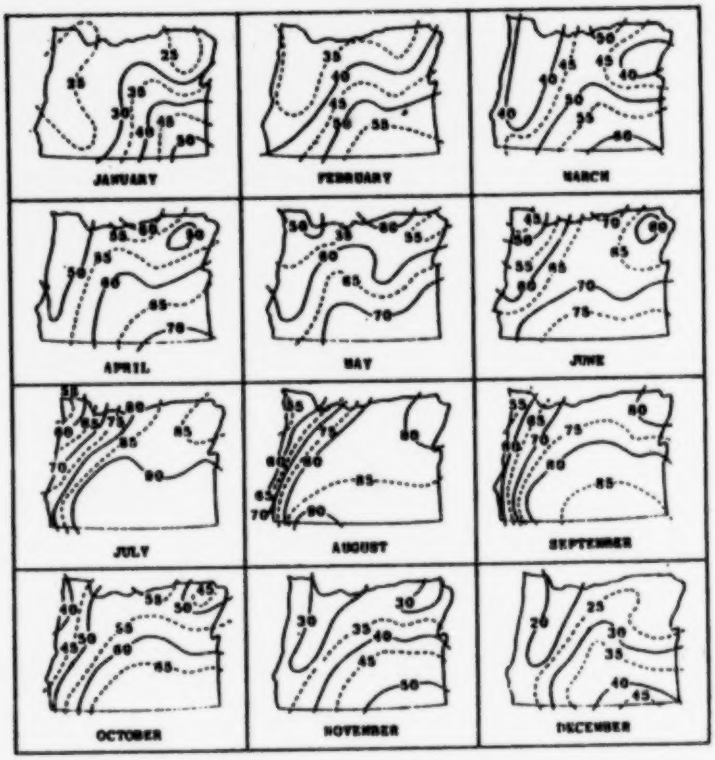
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

Figure 19. Monthly Average Percent of Sunshine in Oregon (After Sternes)

Characteristic climatological regions, regions with characteristics different from that in the mid-Willamette Valley, exist in Oregon. A U.S. Weather Bureau prepared map showing the regions together with rainfall and evaporation data is included in Appendix A.

Oxygen Production

Algal

Oxygen availability is a most important consideration for aerobic lagoon operation. While detailed studies of biological mechanisms have been made by other investigators, certain tests were conducted in order to determine the effect of the various conditions characteristic of a maritime climate. Since the algae-produced oxygen is the primary source of oxygen, solar energy diurnal variations are reflected in algae-produced oxygen. Evaluation of lagoon condition considering dissolved oxygen at any time is impossible without considering diurnal variation.

Figure 20 shows the oxygen variation typical of a sunny July day with solar energy of 570 gram-calories/ cm^2 per day. Also shown is the oxygen variation for a typical overcast December day, with solar energy of 85 gram-calories per cm^2 per day.

Figure 9 (page 21) shows the variation in solar energy for a day's period averaged for the summer and winter months. The magnitude of oxygen variations was found to be somewhat similar to the curves shown, and can be seen by comparing curves in Figure 9 and Figure 27.

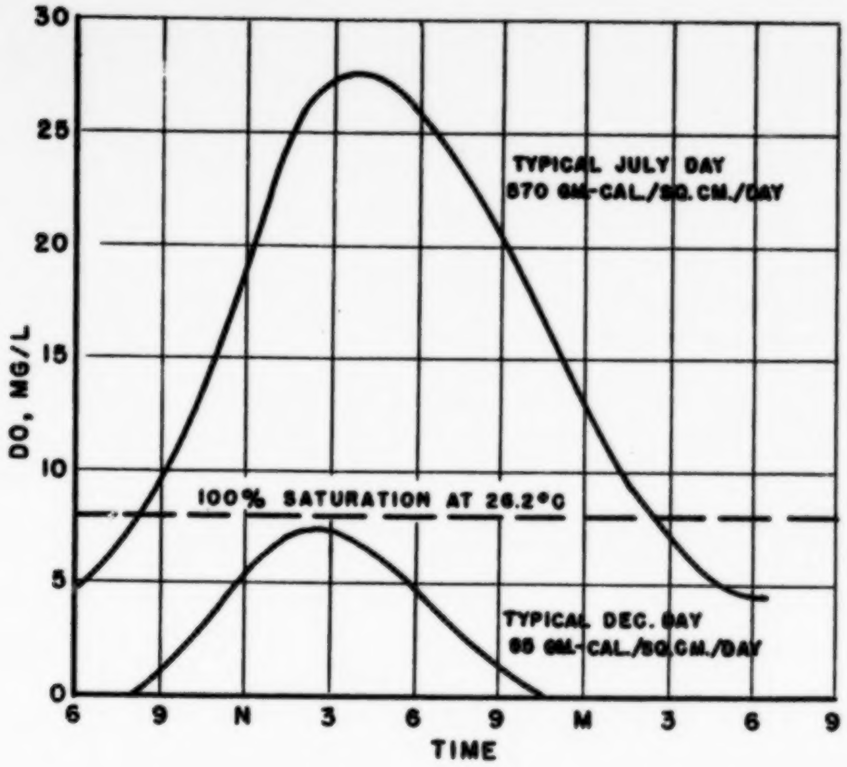

Figure 20. Diurnal Oxygen Variation at Lagoon Surface

Production of oxygen was determined by the standard dark-light bottle test. Figure 21 compares oxygen production with depth on a January day with a light energy of 177 gram-calories/ cm^2, temperature 8.7°C, wind 1.50 mph-SW and precipitation 0.08 inches. Plankton present on that date in terms of ppm by wet volume were chlomydomonas 1.2 ppm and scenedesmusamatus 7.2 ppm. It was found that approximately 65 per cent of the oxygen production occurred in the first 12 inches of depth. Justification of greater depths must, therefore, be based largely upon sludge storage, aquatic weed control and storage for effluent discharge control.

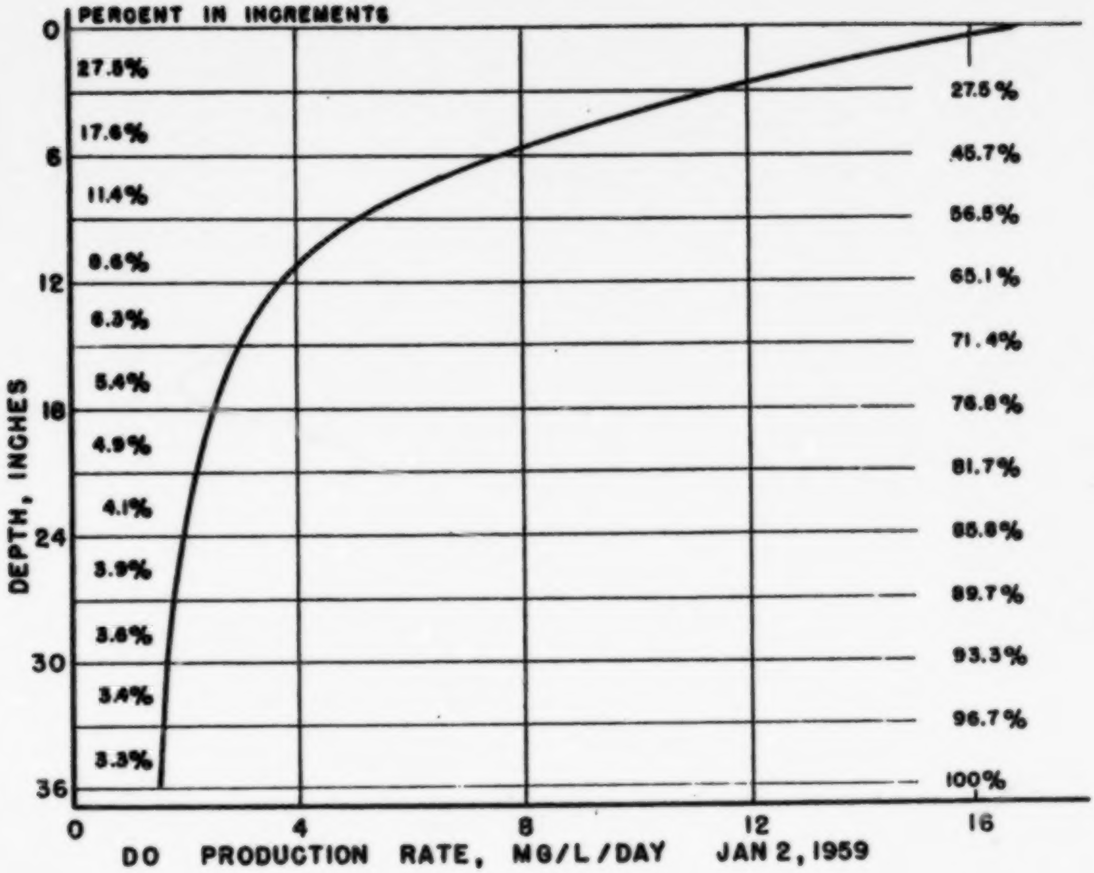

Figure 21. Oxygen Production vs Depth

Oxygen production in other depth increments and its variation throughout the day is shown by Figure 22. It again will be noted the significant production occurs in the top layer.

The dependence of dissolved oxygen concentration in a lagoon on solar energy can also be noted by comparing Figures 20 and 22.

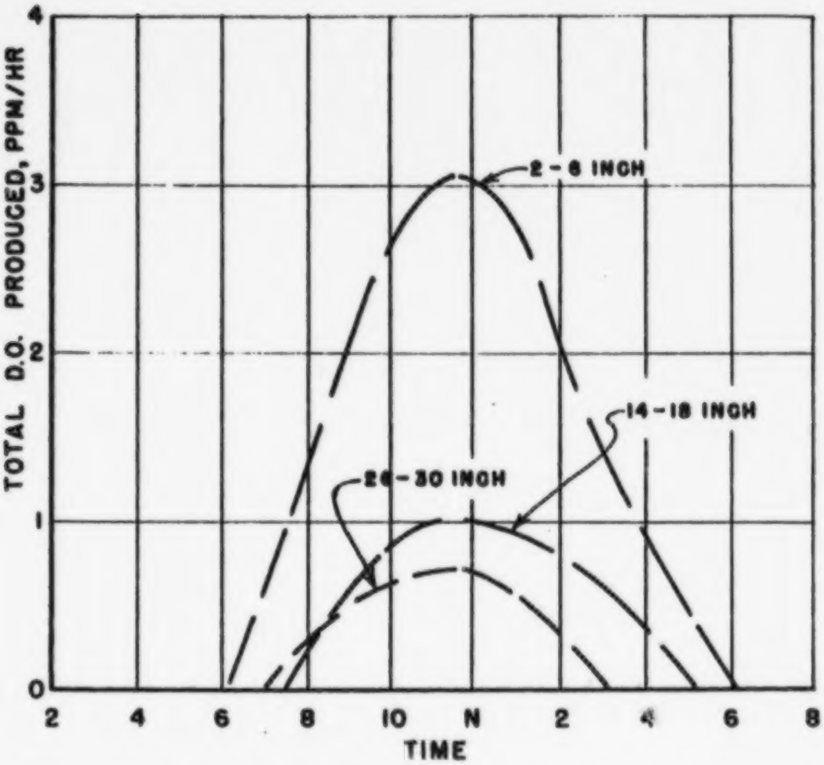

Figure 22. Diurnal Oxygen Production at Indicated Depths - Dec 23

Because algal population is so important to oxygen production, an effort was made to identify the most prevalent species and to count and measure volume of plankton in the two cells. Results as to types and numbers and the methods used in making these determinations may be found in Appendix D under the section titled "Plankton Enumeration."

Reaeration

Reaeration at the lagoon surface by transfer of oxygen across the liquid-air interface is of considerable importance in oxidation lagoons. While the principal source of dissolved oxygen is from photosynthetic production by algae, this mechanism depends upon maintenance of an adequate plankton population.

Several factors may severely limit or destroy phytoplankton growth. These include toxic materials, overloading, large blooms of rotifers or crustacea, exhaustion of nutrients, inadequate solar radiation and other environmental changes unsuited for good algal production.

A major source of trouble was encountered in the experimental oxidation lagoon during periods of introduction of highly colored beet canning wastes, which severely increased the light extinction coefficient and, hence, algal activity. During any period of low oxygen production by algae, reaeration from the surface is the principal source of oxygen.

The gas transfer equation was used to study surface reaeration. The equation

$$dD/dt = -K_2D$$

where D is oxygen deficit at the observed temperature or the difference between the saturation value and the observed dissolved oxygen present. dD/dt is the rate of change in deficit with time. Since dD is proportional to change in dissolved oxygen, d(DO), the equation may be written in terms of weight of oxygen, dw, as uptake in pounds of oxygen per surface acre per 24-hour period for the 3-foot lagoon.

$$dw = \frac{d(DO)(43,560)(62.4)(3)}{1,000,000}$$

$$dw_{lb} = d(DO) \times 8.15$$

The equation becomes

$$\frac{dw}{dt} = \frac{d(DO)\ 8.15}{dt} = K_2D$$

If dt is in hours, K_2 has the units of reciprocal hours and the total uptake in terms of pounds of dissolved oxygen transferred per surface acre per day at steady state conditions may be calculated by

$$lb/day = K_2D \times 24$$

Since oxygen transfer is affected primarily by mixing within the lagoon, surface winds, and condition of the surface, the initial step was to describe total mass transfer. This was done by employing several light cells each consisting of a clear plastic cell and a surface cover, constructed for placement in the lagoon. Figure 23 is an illustrative sketch of the experimental apparatus.

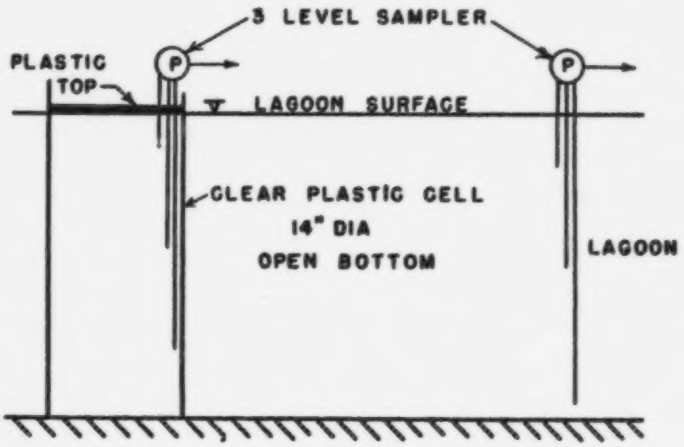
3 LEVEL SAMPLER
PLASTIC TOP
P
P
LAGOON SURFACE
CLEAR PLASTIC CELL
14" DIA
OPEN BOTTOM
LAGOON

Figure 23. Reaeration Study Apparatus

The cell was placed in the lagoon at time zero; selected when the oxygen content was below saturation. Samples were taken at the surface, mid-depth, and near the bottom by a sampling pump to determine the true average dissolved oxygen in each system. At dt time later (normally 4 to 6 hours), samples were again taken to determine the oxygen present. Two curves were thus developed as illustrated in Figure 24.

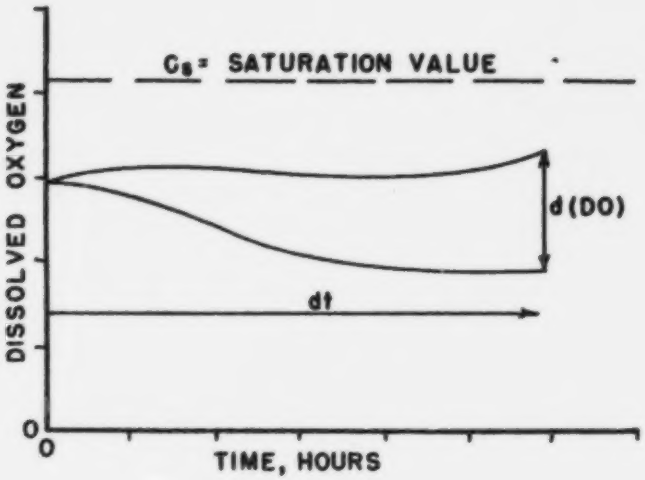

Figure 24. Oxygenation Curves - Lagoon vs Test Cell

Separation of the two curves was the method used as an indirect measurement of oxygen supplied from surface sources. Although feasible, this method was found to be somewhat cumbersome and subject to experimental errors. Typical data obtained in this manner are listed in Table 7.

Table 7. Typical Reaeration Data

Time	Lagoon DO mg/L	Clear cell DO mg/L	Temp °C	Deficit "D" mg/L	$\frac{d(DO)}{dt}$	$\frac{dw}{dt}$	Kr
0	2.65	2.63	3	10.8			
					0.184	1.48	0.143
6	3.05	1.95	5	9.8			
					0.240	1.94	0.206
12	3.80	1.25	5	9.0			

Values of Kr determined by this method ranged from 0.039 to 2.3, with a median value of 0.206. For convenience, a multi-correlation chart (Figure 25) gives the pounds of oxygen that may be transferred per surface acre per day at steady state conditions of constant deficit. While the Kr value of 0.206 requires validation, it is evident that significant oxygen may be obtained from surface sources and would be in many cases sufficient to satisfy the oxygen needed for decomposition (see Sludge Accumulation and Oxygen Demand in Appendix C).

Unfortunately temperatures do not remain average for a period of days or even for a single day. Rapidly changing temperatures, daily and hourly, cause changing decomposition rates of lagoon waste in both the liquid and sludge portions. Therefore, unless constant temperatures can be maintained, it would be doubtful that equilibrium in a lagoon could be reached during the times of low algal activity without at some time creating a demand for oxygen faster than it can be supplied.

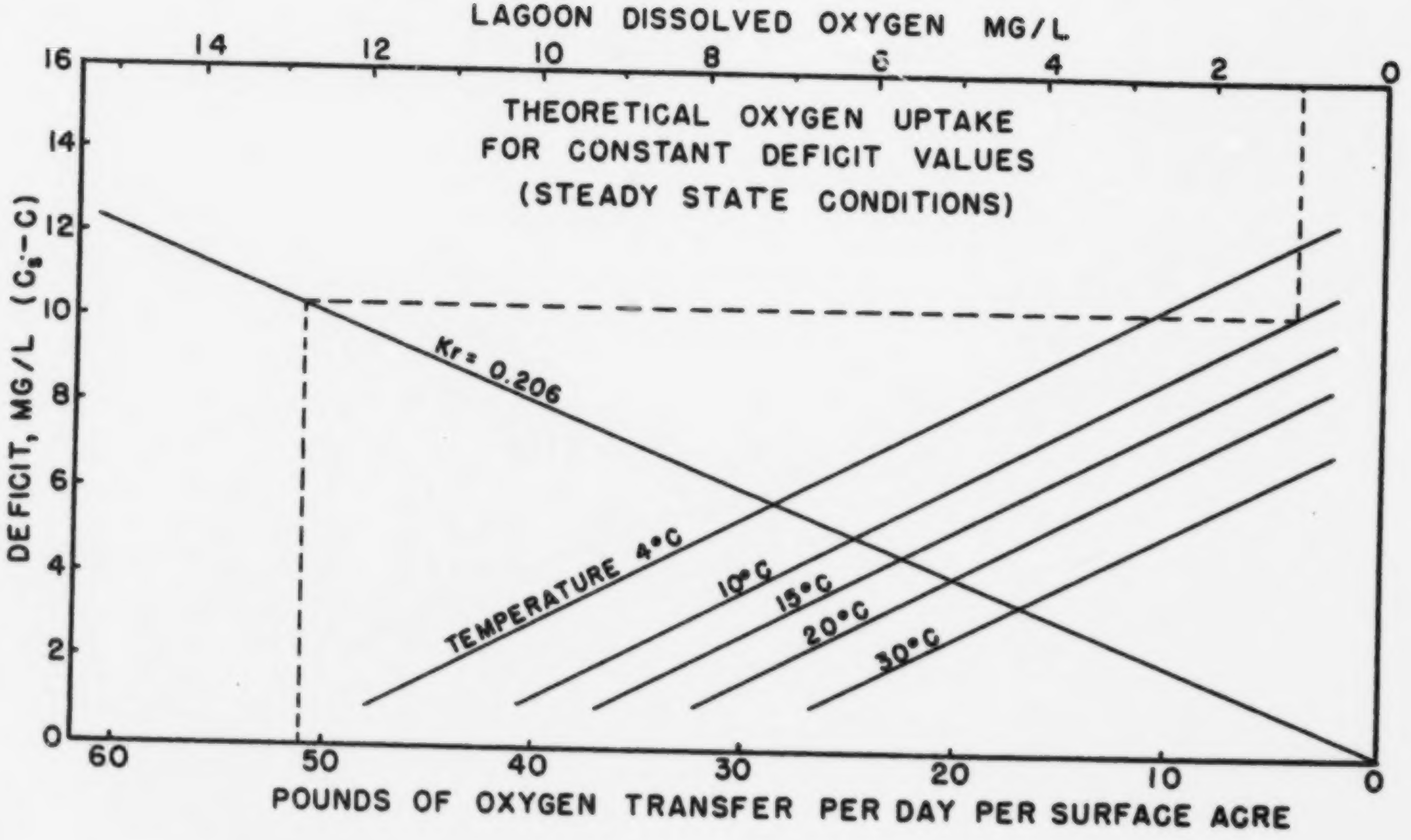

Figure 25. Reaeration Rate - Multicorrelation Graph

Water Balance

Waste water lagoons may be operated as a total retention lagoon with no overflow, as an intermittent drawdown lagoon based on receiving stream requirements, or as a continuously overflowing outfall lagoon.

For a continuously overflowing outfall lagoon the sewage inflow, infiltration and rainfall are balanced by sewage outflow, seepage and evaporation. If infiltration and seepage are minimized then the water balance equation becomes:

$$\text{Influent} + \text{Precipitation} = \text{Effluent} + \text{Evaporation}$$

For complete retention the sewage inflow must balance by natural losses. And if losses to seepage or gains by infiltration are again minimized the waste water balance equation becomes:

$$\text{Influent} + \text{Precipitation} = \text{Evaporation} + \text{Change in Storage}$$

In a maritime climate such as that in western Oregon, the annual rainfall exceeds the evaporation, however, much of the rainfall occurs during the winter months, while most evaporation occurs during the summer months from May through September.

Figure 26 shows net precipitation minus evaporation for summer months in Corvallis as determined from 25 years of records and by evaporation pan studies with lagoon waste water. The curve of precipitation minus evaporation most nearly illustrates a water balance.

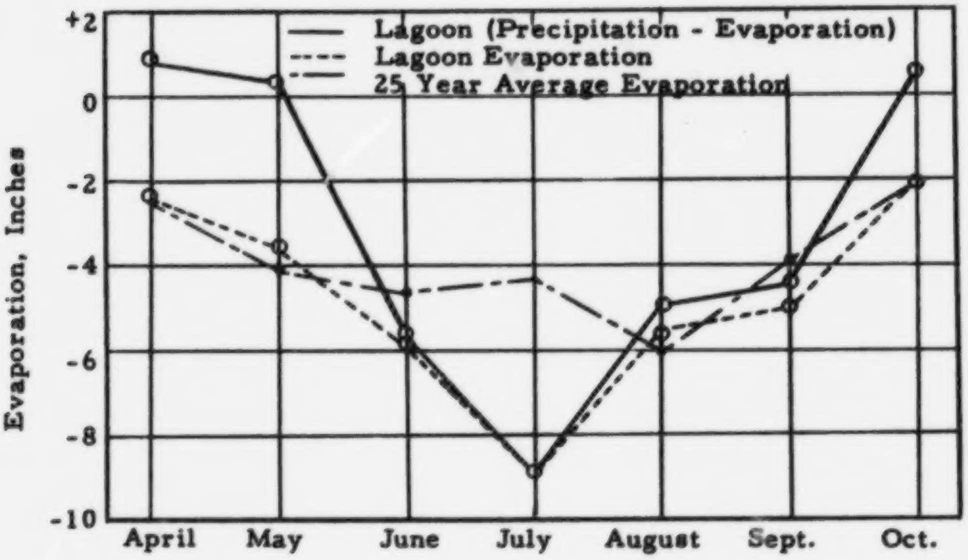

Figure 26. Water Balance

There are certain advantages in operating a lagoon as an intermittent drawdown lagoon. Discharge effluent during the winter or rainy season has the advantage of a high dilution factor of a receiving water course. Storage of effluent during the summer or dry season has the advantage of adding no organic and pollutional load to the receiving stream during the period of low flow and high recreational use.

Figure 27 shows the gallons and depth of waste water produced for population served per acre of lagoon surface, at several different per capita flows, for the four summer months.

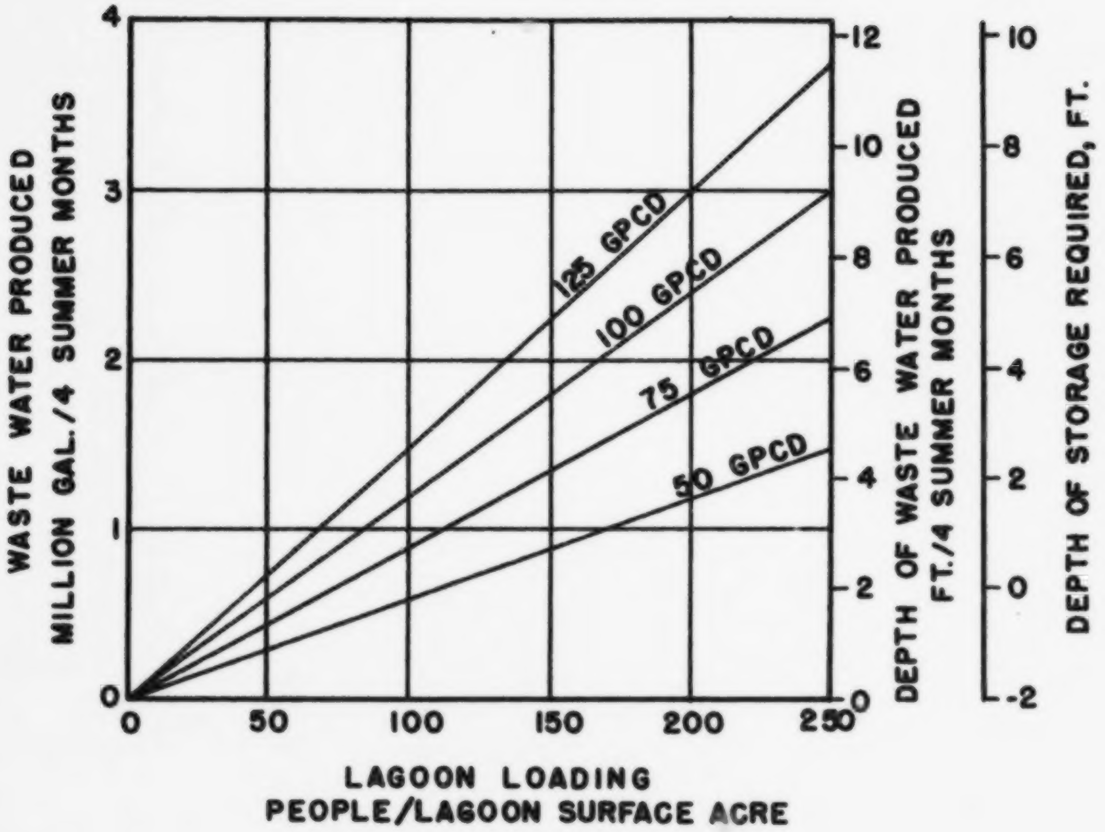

Figure 27. Fluid Depth vs Population Equivalent for Different Per Capita Flows (for 4 summer months)

If the practice of storage during the four critical summer months is to be followed for a lagoon loading rate of 200 people per acre and 100 gallons per capita per day, the total depth of waste water would be 7.35 feet of depth as shown in Figure 28. Subtracting the expected evaporation during that period of time would then give the necessary storage. For this example, the change in depth for added necessary storage would be approximately 5.35 feet.

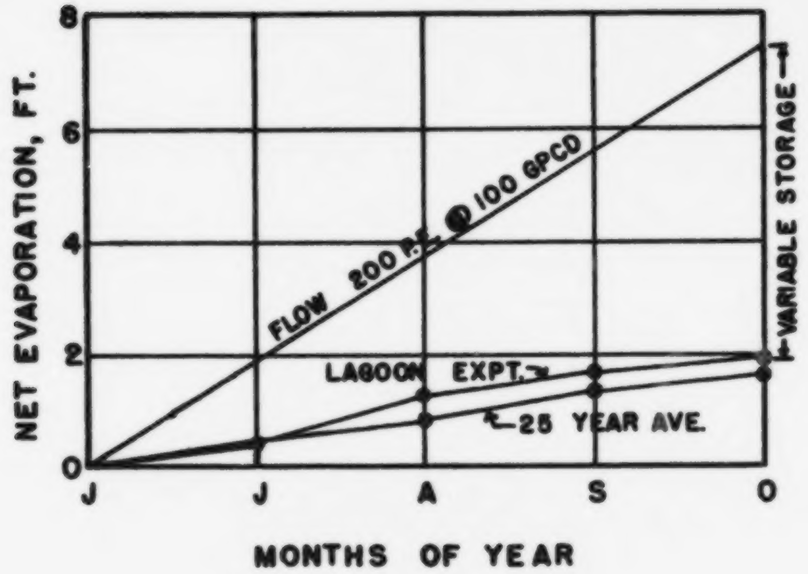

Figure 28. Summation of Net Evaporation for Summer Months, Corvallis Experience

A multiple level outlet such that the lagoon could be operated at 2.0 feet depth in late spring with a high water outlet at 7.35 feet would accomplish the storage benefit without an effluent discharge to the receiving stream at low flows.

Variable storage necessary to satisfy needs for numbers of persons served and per capita rates other than those used in the example can be determined using plots in Figure 27.

Table 8 was prepared from data that were collected in evaporation pan studies at Oregon State University. Evaporation data have been converted to equivalent persons per surface acre on the basis of 100 gallons per capita per day or 3000 gallons per capita per month. The volume removed by evaporation necessitates additional or "make up" water if a lagoon is put into operation during the summer months, especially when the population equivalent at beginning operation is considerably less than the design population equivalent.

Table 8. Water Balance Data

Month	Precipitation-evaporation Equivalent inches	gallons/acre	person/acre
June	-5.59	152,188	50.7
July	-8.94	243,392	81.1
August	-5.00	136,125	45.5
September	-4.29	116,795	38.9
4 Months Total	-23.82	648,500	216.1

The Effect of Effluent on Receiving Streams

A study of the effect of waste water lagoon effluent upon a simulated receiving stream was undertaken to assess the problems that might be introduced by chlorination of the lagoon effluent. Previous studies had indicated that disinfection of the effluent resulting in algal death caused an apparent increase in the BOD of the effluent, with the magnitude of this increase being quite variable. Changes in this relationship, together with other physical-chemical relationships were the subject of the receiving stream study.

A simulated stream was constructed consisting of four channels with paddle wheels to recirculate water (See Figure 29).

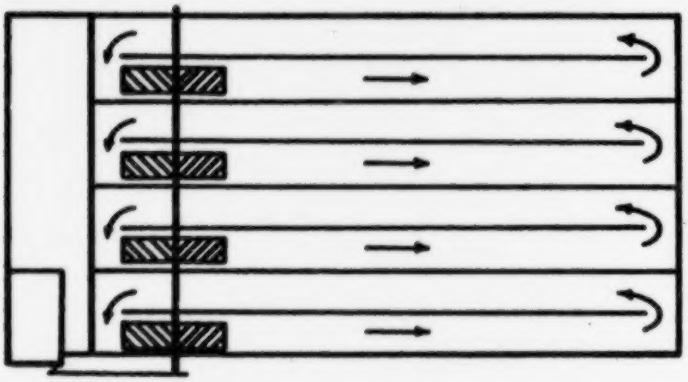

Figure 29. Flow Diagram of Simulated Stream

Since it was not practical to construct a model of sufficient length to simulate field conditions, the approach was to consider each unit as a mass of water moving downstream in a river subjected to conditions of light, temperature and turbulence. A fluourescent lighting system was suspended over the simulated stream which produced an illumination of 550 foot candles at the water surface. Lights were operated on a time clock system. Temperature of the system was $14.5^{\circ}C \pm 1^{\circ}C$. Reaeration studies conducted by depressing oxygen values and calibrating uptake rates indicated the reaeration constant "K_2" for the system was 0.678/day.

Studies consisted of following physical-chemical changes in the system throughout a time period corresponding to a flow time downsteam from a waste outfall. Values of ammonia, nitrite, and nitrate nitrogen; algae concentration, ortho-phosphate, polyphosphate, BOD reaction velocity constant "K", and ultimate BOD remaining, "La", were determined at times up to

7 days. These tests were conducted simultaneously on river water, river water with unchlorinated lagoon effluent, and river water with chlorinated lagoon effluent. Different ratios of lagoon effluent to river water were used. Results of a typical test series are shown in Figures 30 through 32 and Figures E1 through E7 in Appendix E.

Disinfection of the chlorinated series was accomplished by introducing chlorine into a sample of lagoon effluent in a quantity sufficient to produce 0.5 mg/ L residual after contact time of 15 minutes. The chlorinated effluent was then introduced to the simulated stream, together with Willamette River water.

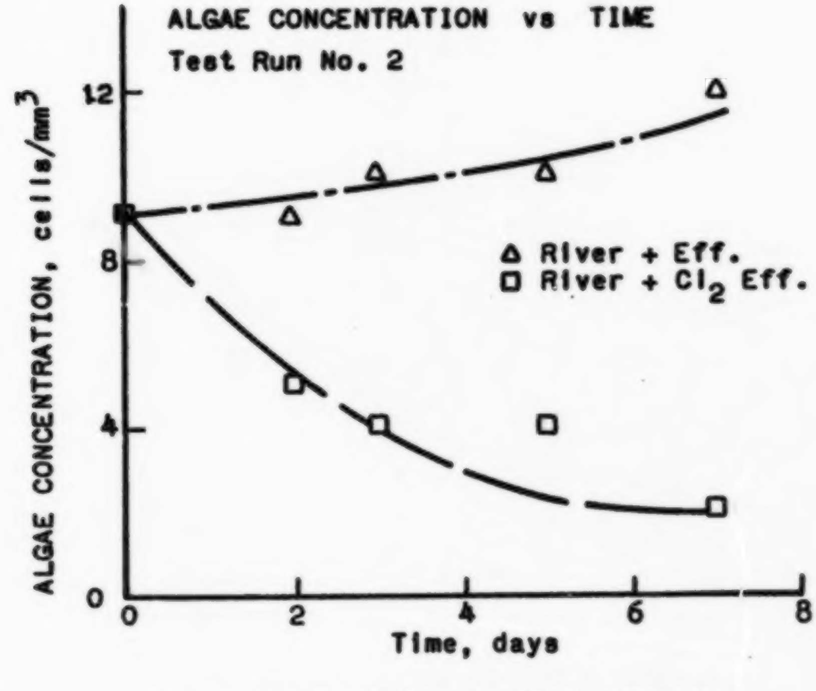

Figure 30. Variations in Algal Population

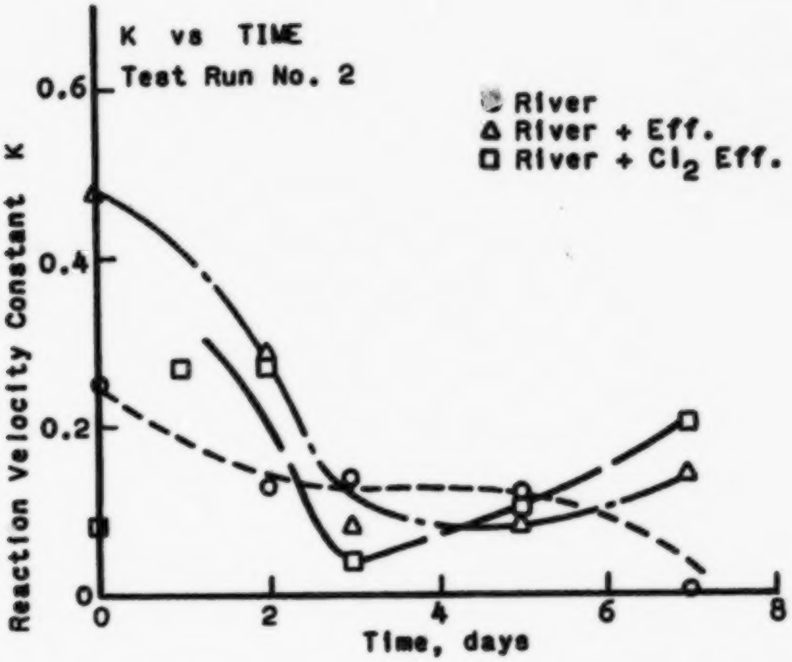

Figure 31. Variations in BOD Reaction Velocity Constant K

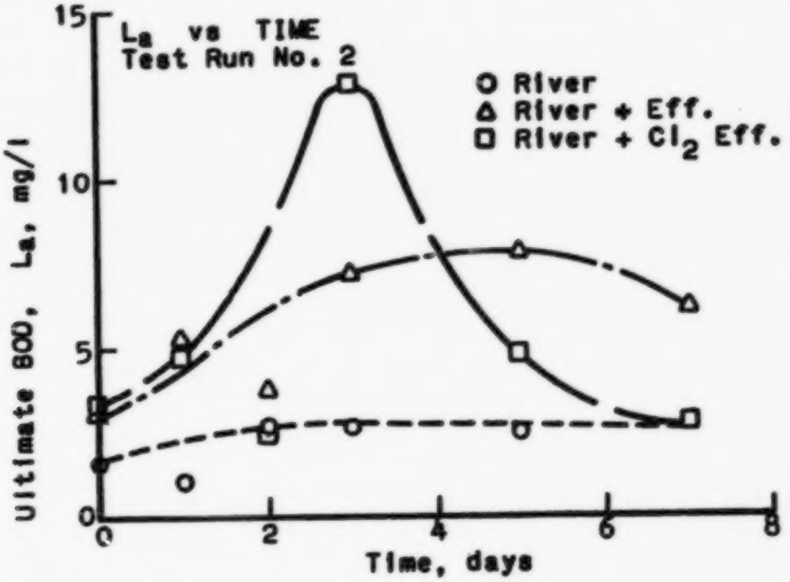

Figure 32. Ultimate First-Stage BOD Remaining at Times Indicated

River water by itself had insufficient nutrients to support a significant algal population. While a sparse plankton population was present, additional growth did not take place. Introduction of unchlorinated effluent added both a significant algal population and needed nutrients. An increase in plankton population resulted during the unchlorinated test. While the same level of nutrients were added to the simulated stream in the chlorinated test channel, a gradual decline in algal population was noted (Figure 32).

It is interesting to note that the decline was quite gradual indicating possible long-term toxicity effects of the initial chlorination upon the algae. Their ability to reproduce in the stream was markedly diminished.

BOD reaction velocity constant "K" determinations were made upon samples from the test channels at various time increments and are shown in Figure 31. The ultimate first-stage BOD "La" value exhibited by water from the simulated streams was determined at the same time increments and is shown in Figure 32.

It can be noted that the ultimate BOD of the river water was quite stable throughout the test, indicating a balance in the biological system of the river. The ultimate BOD of the water in the channel that contained river water plus unchlorinated lagoon effluent exhibited an increase during the test series. The ultimate BOD of the water in the channel containing chlorinated effluent demonstrated an initial increase reaching a maximum between the 2nd and 3rd day for all test series. A decrease in ultimate BOD followed which can be described by an expotential curve.

Since the value of L_a measured at various times represents the amount of decomposable organic matter present, "K" represents a rate of reaction. The first order equation of BOD satisfaction may be applied and a rate of utilization expressed as $\Delta L/\Delta t = KL_a$, yielding use rates existing at the time of sampling. Table 9 is a listing of such values for the test series illustrated.

Table 9. Utilization Rates vs Time

		(1) Chlorinated			(2) Unchlorinated		Ratio
Time days	K	L	KL	K	L	KL	KL(1)/KL(2)
0	-	3.4	-	0.48	3.0	1.44	-
1	0.32	4.8	1.53	0.41	4.2	1.74	0.88
2	0.2	8.4	1.68	0.28	6.0	1.68	1.00
3	0.04	12.8	0.10	0.12	7.2	0.86	0.12
4	0.08	7.8	0.62	0.08	7.8	0.62	1.00
5	0.10	5.0	0.50	0.08	8.0	0.64	0.78
6	0.15	3.0	0.45	0.10	7.5	0.75	0.60
7	0.20	2.6	0.52	0.14	6.0	0.84	0.62

Because of the large number of determinations necessary to construct these data, it was not possible to complete a sufficient number of test series to justify specific conclusions. However, a few general observations may be made as follows:

1. Disinfection with chlorine results in destruction of the plankton population and contributes additional decomposable organic material to the receiving stream.

2. A period of 2 to 3 days was required in the simulated stream for the full effect of the increased load to materialize as measured by ultimate BOD.

The reaction velocity constant is usually lowest at this time, resulting in a rate of utilization $\Delta L/\Delta t$ that is not materially higher than the initial rate. This lag may be partially attributed to time required for dead cells to become available as a bacterial food.

3. Biochemical oxygen demand (BOD) is not a reliable measurement of pollutional load for wastes of this nature unless a detailed and complete analysis is made to determine the portions of BOD due to bacterial respiration in the metabolism of organic wastes present, respiration of plankton population present and bacterial respiration in utilizing organic material contributed by dead plankton cells. Methods of doing this with ease or with certainty have not yet been devised. Values of the variation in "K" and L with time, in addition to other variables discussed above, must also be determined for evaluation of BOD data.

Data on nitrogen and phosphate transformations as well as BOD-time test information are presented in Appendix E, Figures E1 through E7.

Receiving stream studies were extended to determine at what point chlorine might be added in a series of lagoons to best accomplish kill of fecal bacteria and least affect lagoon operation.

A simulated series lagoon system was constructed having four rows of four cells each. Each cell was approximately ten inches by fourteen inches in surface area and approximately six inches deep (See Figure 33). The The fluorescent lighting system described in the first part of "Receiving Stream Studies" was used as a light energy source. The illumination produced at the water surface was 550 foot candles. The light system was controlled by a time clock system. Temperature of the system was approximately 23°C ± 2°C.

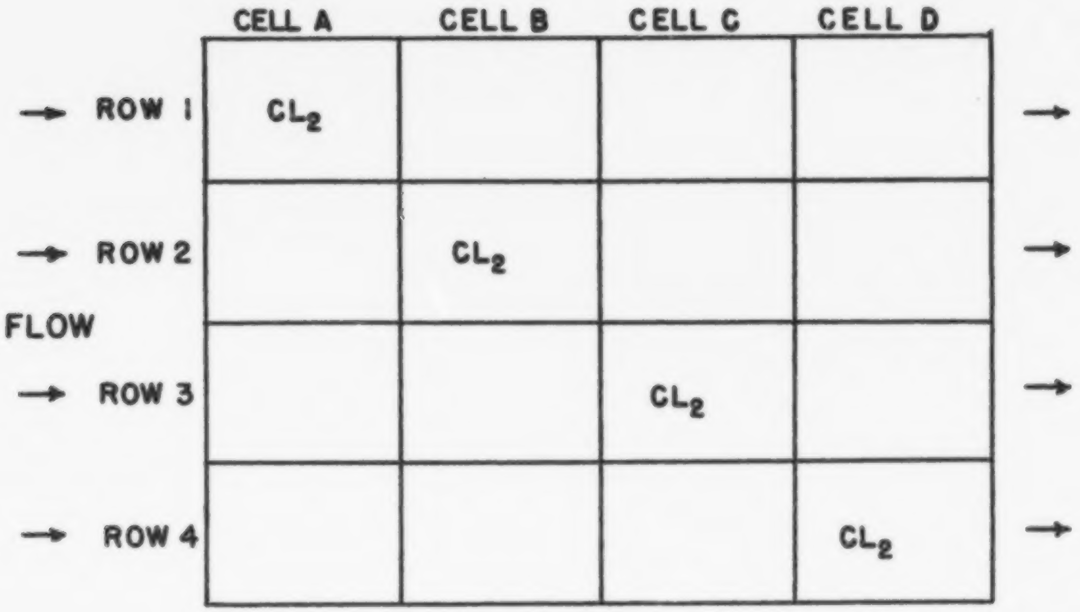

Figure 33. Series Lagoon Model for Receiving Stream Studies

The first cell in each row was loaded with a synthetic food made up with a liquid portion from the lagoon effluent, and loaded at the rate of 30 pounds of five-day BOD per acre per day. Volumetric loading was such that the detention time of each cell was six days or 24 days for the series of four cells. Losses to evaporation were made up by adding distilled water to the system to maintain the six inch water level.

Disinfection by chlorine was performed on the portion transferred to the first cell in row one to the second cell in row two to the third cell in row three and to the fourth cell in row four. Chlorine required for disinfection in this portion of the study was obtained by adding that necessary for a residual of 0.5 mg/L after 30 minutes of contact time. Samples for testing were collected at 10 a.m. each morning. The tests conducted on the portion transferred each day were DO, BOD, algal population and specie and coliform density. The data collected from this system are presented as averages in Figures 34 and 35.

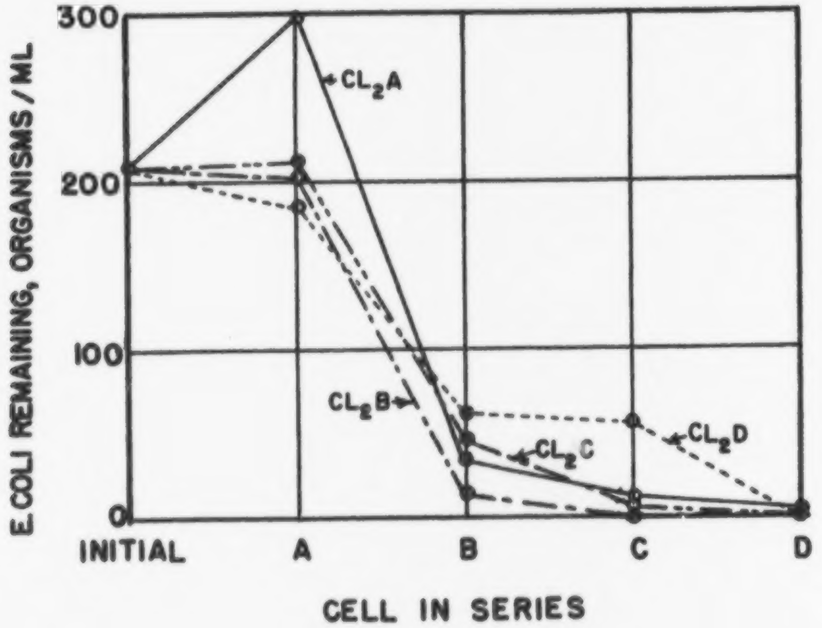

Figure 34. E. Coli Remaining in Each Cell with Different Points of Chlorination

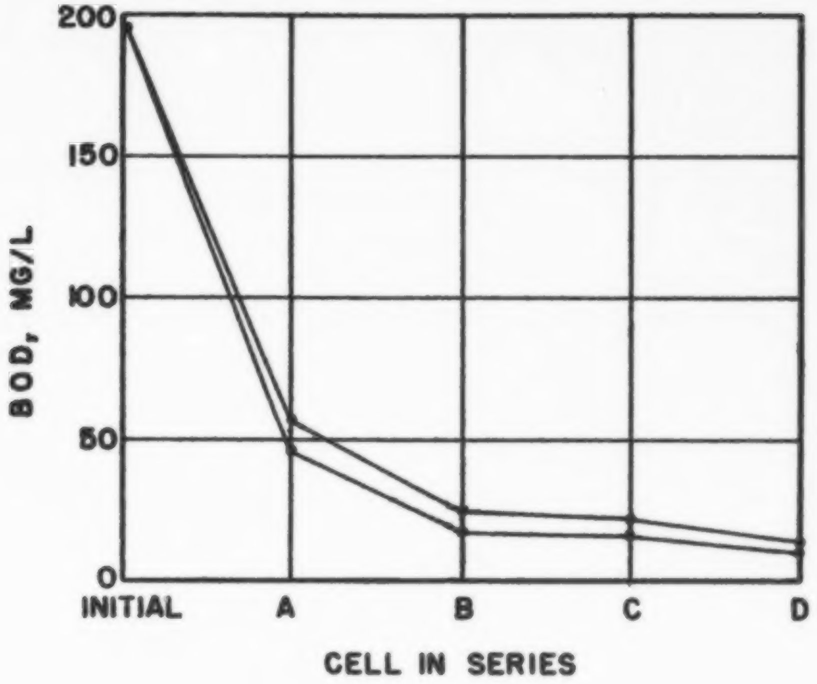

Figure 35. Range of Average BOD's for Different Points of Chlorination

Similar coliform densities were obtained in each series (See Figure 34). An apparent coliform regrowth occurred in cell A series one, (the influent was chlorinated as added to this cell) but disinfection of the influent to cell B in series two after a six-day retention in cell A displayed no such regrowth characteristic nor did a regrowth characteristic occur in any other series.

Except for series one where disinfection was performed on the influent to the first cell (A), the greatest number of coliform organisms remaining were in each case in the unchlorinated series.

Results of five-day BOD determination performed on each cell are shown in Figure 35. Maximum and minimum values for each series are shown for the four cells in each series. It can be noted that no significant difference existed regardless of the condition of chlorination.

Information on effluent condition and chlorine required to affect a 0.5 mg/L residual after 30 minute contact time is presented in Table 10.

Effluent from series one and two was observed to be clearer in most cases than was the effluent when chlorination was practiced later in the series.

Table 10

Series	Pt. Cl_2 introduced	Cl_2 Resid. on portion to cell @ 30 min.	Cl_2 Reg'd Range	Effluent Condition	
				Wet vol. ml/100 ml	Appearance
Row 1	Cell A	0.5 mg/L	4-8 mg/L	0.02	clear
Row 2	Cell B	0.5 mg/L	4-8 mg/L	0.1	clear
Row 3	Cell C	0.5 mg/L	3-7 mg/L	1.0	green
Row 4	Cell D	0.5 mg/L	1.5-6 mg/L	1.0	green

If the results of this model study are applicable to a prototype and if the appearance of the effluent is the criteria, then chlorination would best be practiced by adding chlorine early in a series operation. If, however, the economics of required chlorine to affect a 0.5 mg/L residual is the criteria then chlorination late in the series would best be done because no appreciable differences were noted in the number of coliform organisms nor in the final BOD remaining in any series.

An interesting result of this experiment was that similar reductions in numbers of coliforms existed in all series. This could indicate that employing a physical barrier to eliminate short circuiting could have a pronounced effect on coliform reduction and would support reason for employing series cell lagoon operation.

Design Criteria

All data collected from the single cell operation of the experimental lagoon were tabulated in such a way that statistical analyses to determine certain correlations might be performed. The analyses were made on an IBM 1620 computer employing a stepwise regression analysis program as a method to test for correlation.

Data analysis included correlation runs using solar radiation measurements, temperature, pH, DO, BOD, suspended solids, and organic loading. The best correlation was found to exist in comparing the ratio of organic load $(\frac{Po}{P})$ influent over effluent to the organic loading (Po) of the influent in terms of pounds of five-day BOD per acre per day calculated using the water loss or gain due to evaporation or precipitation. From this correlation, equation 1-1 was determined

$$P = 1.90 \ Po^{0.434}$$

A plot of this equation with an 80 percent confidence interval appears in Figure 36. Experimental data from which this comparison was made was from both summer and winter operation which would account for the seemingly acceptable operation at the higher loading values. Loading values as high as

150 pounds of five-day BOD per acre per day produced an acceptable lagoon condition during summer or high solar energy periods.

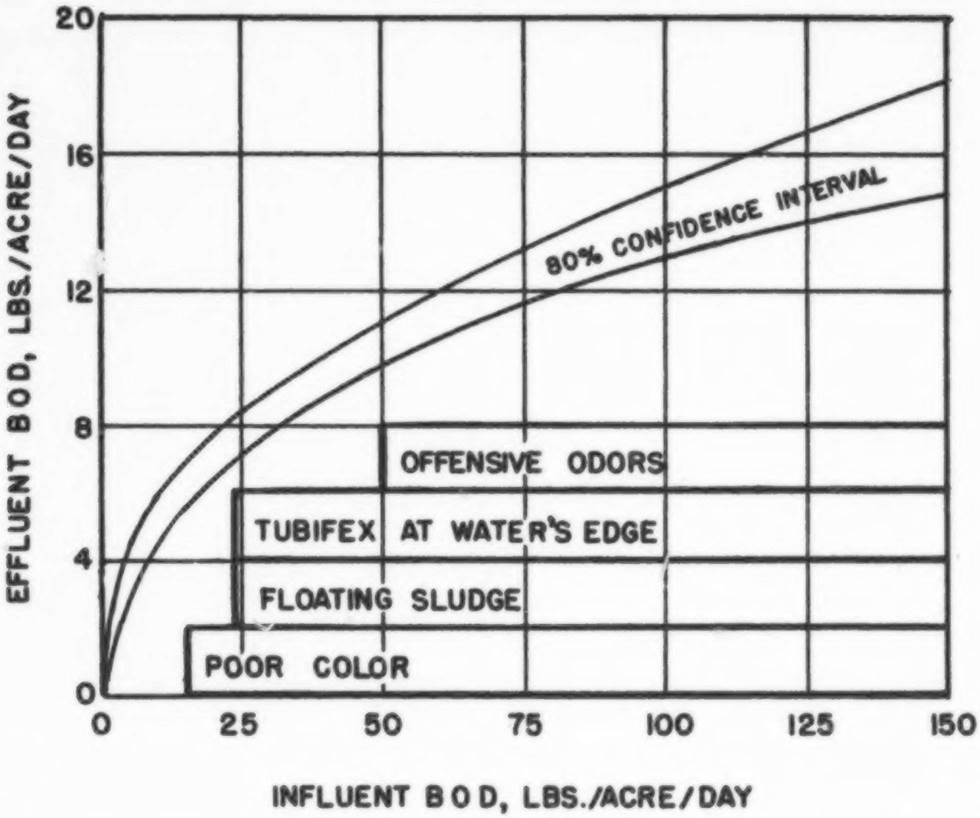

Figure 36. Effluent vs Influent Showing Thresholds of Poor Condition

In determining acceptable loading criteria, it is first necessary to establish what constitutes acceptable operation. Organic load in the effluent at a particular influent loading rate might be acceptable by itself but if a nuisance is created by odors for certain periods of the year, the over-all operation may be considered unacceptable. In other cases odor might not be objectionable for certain periods through the year, but the effluent organic load being placed on the receiving stream could be unacceptable.

Thus, there would then seem to be, not including bacteriological quality, two criteria for determining loading. The first, effluent quality (organic load) with reference to the receiving stream. And the second, the aesthetics of the lagoon unit, odor being the principle factor.

Results of this study show that indicators of poor condition occurred at very low loadings. Poor color associated with deteriorating condition occurred at influent organic loadings as low as 15 pounds of five-day BOD per acre per day. Floating sludge and tubifex at water's edge were noted at organic loading values as low as 24 pounds of five-day BOD per acre per day. Odors, associated with an anaerobic condition, were observed at organic loadings as low as 50 pounds of five-day BOD per acre per day.

These observations as to condition have been added to Figure 36. Loadings corresponding with the listed conditions are intended to indicate "threshold" values for that condition at a critical period in this climatological region. The period of time that a particular condition would exist with loading continued at the same rate would depend on climatic conditions.

A decrease in cloud cover with a resulting increase in solar radiation, an increasing wind condition with a resulting better mixing and oxygen gain from reaeration or a drop in temperature to slow down the decomposition rate of the waste could change an unacceptable condition to one of acceptability.

For the experimental facility, any organic loading that produced an odor free operation was assumed to be acceptable. Any loading that produced odors associated with anaerobic conditions was deemed unacceptable.

The organic loading of less than 50 pounds of five-day BOD per acre per day was found to be that maximum loading value that could be sustained over a winter period without causing odors. Whether this approximately 80% BOD removal that occurs at a loading rate of 50 pounds of five-day BOD per acre per day (See Figure 36) is adequate would depend on the oxygen resource of the receiving stream.

The loading value of 35 pounds of five-day BOD per acre per day which is now recommended as a maximum loading by the Oregon State Sanitary Authority would seem to be a reasonable loading value in keeping with the sound engineering practice of allowing for a margin of safety.

Cost Analysis

One of the most favorable reasons for using lagoons for treating wastes is the low operational cost. Initial construction costs run about the same as conventional secondary treatment plants (See Table 11), but the operational and maintenance costs are far lower. Figures 37, 38 and 39 give the initial per capita costs for various design population equivalents for secondary treatment plants, primary treatment plants, and raw sewage lagoons respectively. The plotted points were taken from contracts let in Oregon and do not include land costs (reference OSSA reports). The lines through the points are the lines of best fit as determined by Clare & Wiener for U.S.P.H.S. Region VI. Treatment works and land cost are included in these fitted lines.

Table 11. Cost Data

A. Embankment

$0.66 per C. Y.
Includes stripping from lagoon area, placing, and compaction in lifts of six inches.

B. Land

$1,000 per acre

C. Fence

$1.65 per lineal foot plus approximately $100 for gate structure.

D. Clear and grubb

$300 per acre
Includes stripping and removing all organic matter and other objectionable material to a depth of not more than 12 inches.

E. Soil sealing

$0.06 per S. Y
Includes scarifying lagoon bottom and compaction to a depth of six inches.

To determine what extra costs were involved by allowing no effluent during the summer months, as suggested in the section on Water Balance, an analysis was made calculating the per capita costs for various loading rates and retention periods for different design populations. The analysis was made using a typical design and includes land costs, earthwork costs, soil sealing costs, and fencing costs. Unit costs used for this analysis are presented in Table 10. No provisions were made for access roads, inlet or outlet

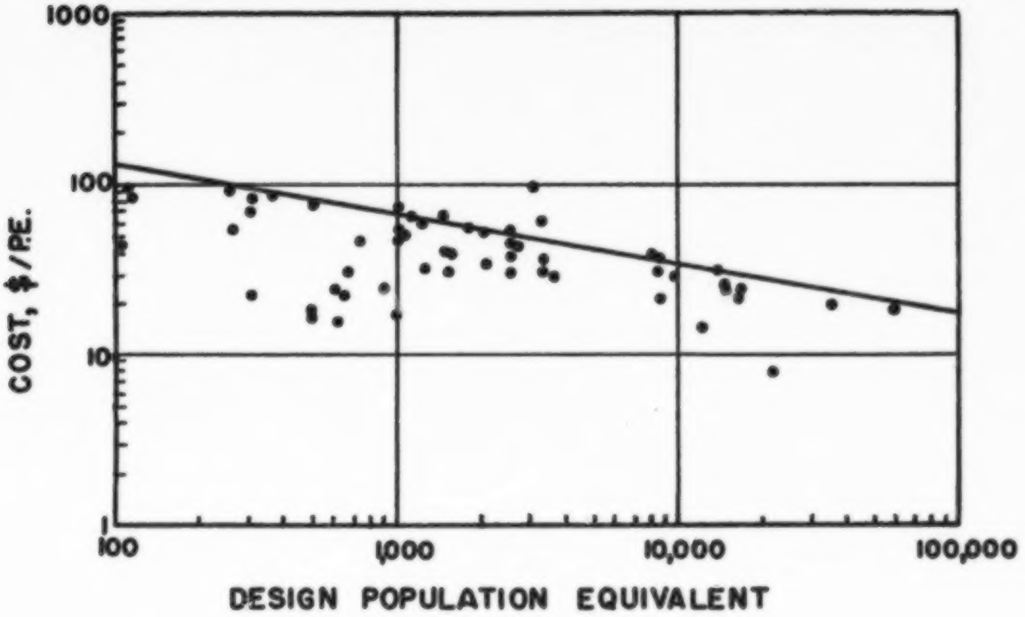

Figure 37. Per Capita Cost vs Design Population for Primary Plus Secondary Treatment Plants

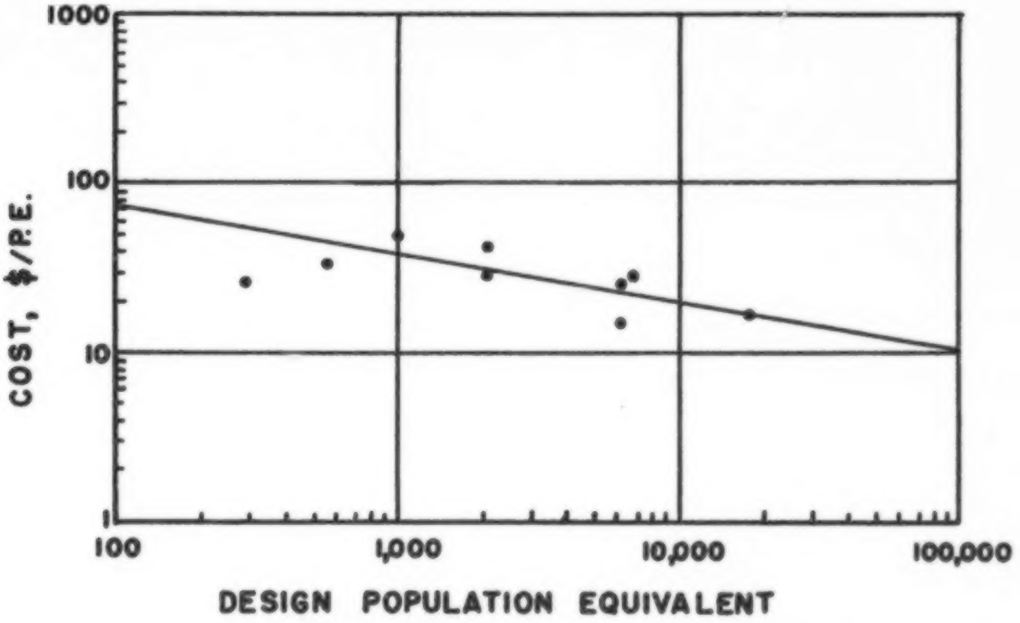

Figure 38. Per Capita Cost vs Design Population for Primary Treatment Plants

structures, bank protection, or disinfection equipment. The cost values thus shown in Figure 40 and Table 12 are comparative only and are not intended to provide specific cost data.

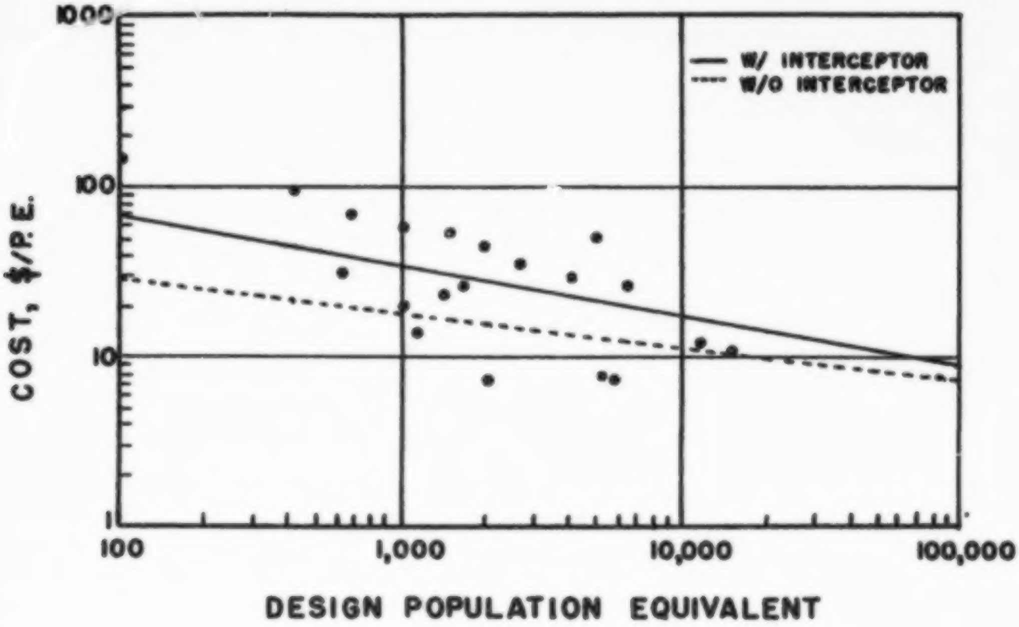

Figure 39. Per Capita Cost vs Design Population for Raw Sewage Lagoons

Table 12. Waste Treatment Cost Comparison from Figures 37, 38 and 39.

	Per Capita Costs - in Dollars					
			Lagoon			
		Primary &	inflow-outflow		No discharge	
P.E.*	Primary	Secondary			1 May-30 Sept.	
			20	40**	20	40
1,000	40	70	28	16	41	33
5,000	30	50	24	14	35	22
10,000	22	40	17	10	23	17

* P.E. - Population equivalent

** Values 20 and 40 relate to loading rates in terms of pounds of five-day BOD per acre per day

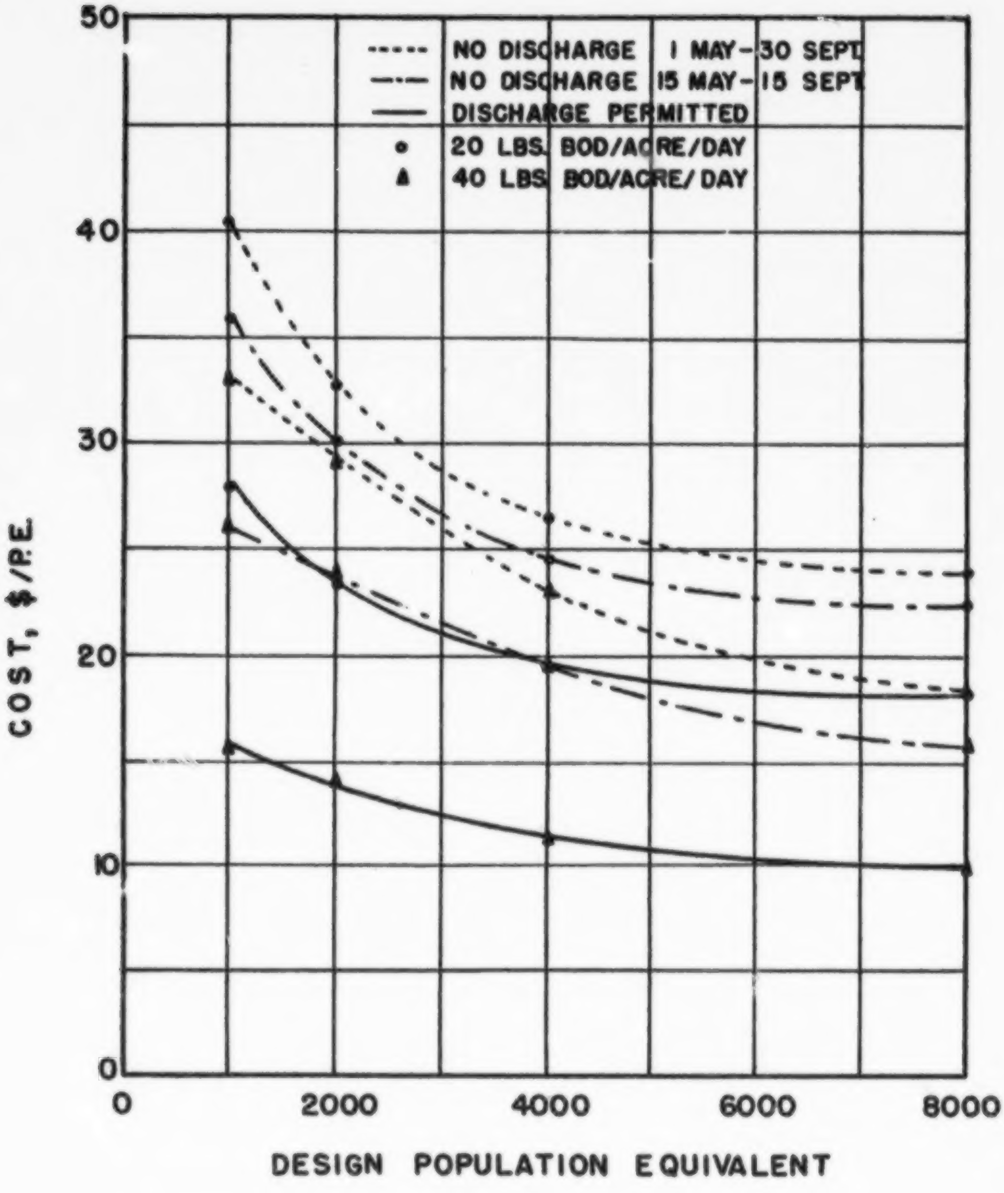

Figure 40. Per Capita Cost vs Population Equivalent for Different Loadings and Different Periods without Discharge

V. CONCLUSIONS

Conclusions drawn and listed below resulted from critical observations and examination of the experimental lagoon, lagoon and river laboratory models and lagoons in operation.

1. Waste water oxidation lagoons may be successfully used for the treatment of domestic wastes in the maritime climate of the Pacific Northwest.

2. Loading criteria for this area of 35 pounds of five-day BOD per acre per day (i.e., population equivalent of 200 persons) as a design value for a summer-winter operation is feasible. This provides for a safety factor of approximately 1.3 which would seem reasonable if odor free and nuisance free operation is to be maintained.

3. Shock loadings four times in excess of the value above can be tolerated for short periods during the summer at times when solar energy is greatest.

4. During times at which lagoon operation is acceptable, about 80 per cent of the organic material applied is removed. When failure occurs (i.e., an odor nuisance associated with anaerobic condition) organic material removal was observed to drop to 20 per cent and lower. Strong correlation between BOD removal and loading rates does not exist. Therefore, BOD reduction is not a reliable measure of lagoon performance.

5. Reductions of coliform bacteria range between 53 and 99.5 per cent. Corresponding numbers remaining in the effluent from a single cell were as

high as 28,000 coliforms per ml. and as high as 2,100 coliforms per ml. in the effluent from the second cell in a two cell series. Survival of coliform organisms is significant to the extent that a potential health hazard exists. It would seem advisable that disinfection of the effluent should be practiced if discharged into a stream above a source of water supply.

6. Some of the organic material in the waste water being treated is transformed into living cells. In addition primary production adds organic material in the form of algal cells. This living organic matter is made available for decomposition when disinfection is practiced. The increase in BOD after disinfection was found to range as high as two times the BOD value obtained when disinfection was not practiced.

7. When three or four cells in series are employed little or no change in the quality of the effluent, except for color, exists regardless of point of disinfection. A clearer effluent results when disinfection is practiced early in the series of lagoon cells.

8. Flexibility may be added to lagoon operation by employing two or more cells designed to operate in series during periods of lighter loading and in parallel during periods of high loading such that the load on the primary cell is controlled within the limit of aerobic operation.

9. Transfer of oxygen from the atmosphere to the lagoon is significant and accounts for the major portion of available oxygen during dark periods, and at times of little or no algal activity. For example, in a

3-foot deep lagoon with wind turbulence causing a transfer coefficient "K" of 2. 06 with a lagoon DO of three mg per liter and a constant lagoon temperature of 20° C, approximately 30 pounds of oxygen may be transferred each day for each surface acre of lagoon.

10. While lagooning requires less operation than conventional treatment methods certain operational tasks are necessary if unsightly and nuisance conditions are to be avoided. Lagoon dikes must be maintained, marginal grass must be controlled and at certain times mosquito larva must be sprayed.

11. Total disposal of effluent during summer months by utilizing evaporation plus storage is entirely feasible for the climatological characteristics encountered in the Pacific Northwest. Details of this approach are given on page 55 of this report. Construction costs of such a facility are approximately equal to the cost of a conventional primary treatment facility having a comparable treating capacity. Design and design costs of such a system must be predicated on local construction costs and local weather conditions.

12. Waste water lagoons are not a solution to all waste water problems. They are, however, an economical means of satisfactorily treating sewage, especially in smaller communities where land is available and land costs are not excessive.

APPENDIX - A

A. SELECTED CLIMATOLOGICAL DATA OF OREGON

B. PREDICTION OF AVERAGE AND DIURNAL TEMPERATURES IN WASTE WATER LAGOONS

C. ANALYSIS FOR SLUDGE ACCUMULATION AND OXYGEN DEMAND IN OXIDATION LAGOONS

D. PLANKTON ENUMERATION

E. NITROGEN AND PHOSPHATE VARIATIONS AND BOD TIME RELATIONSHIPS FOR RIVER MODEL STUDIES

APPENDIX A

SELECTED CLIMATOLOGICAL DATA OF OREGON

Area divisions as shown on the Oregon map in Figure 1-A were made by the U.S. Weather Bureau and are intended to represent characteristic climatological regions. Tables 1A and 2A show monthly precipitation and evaporation values characteristic to those several climatological regions.

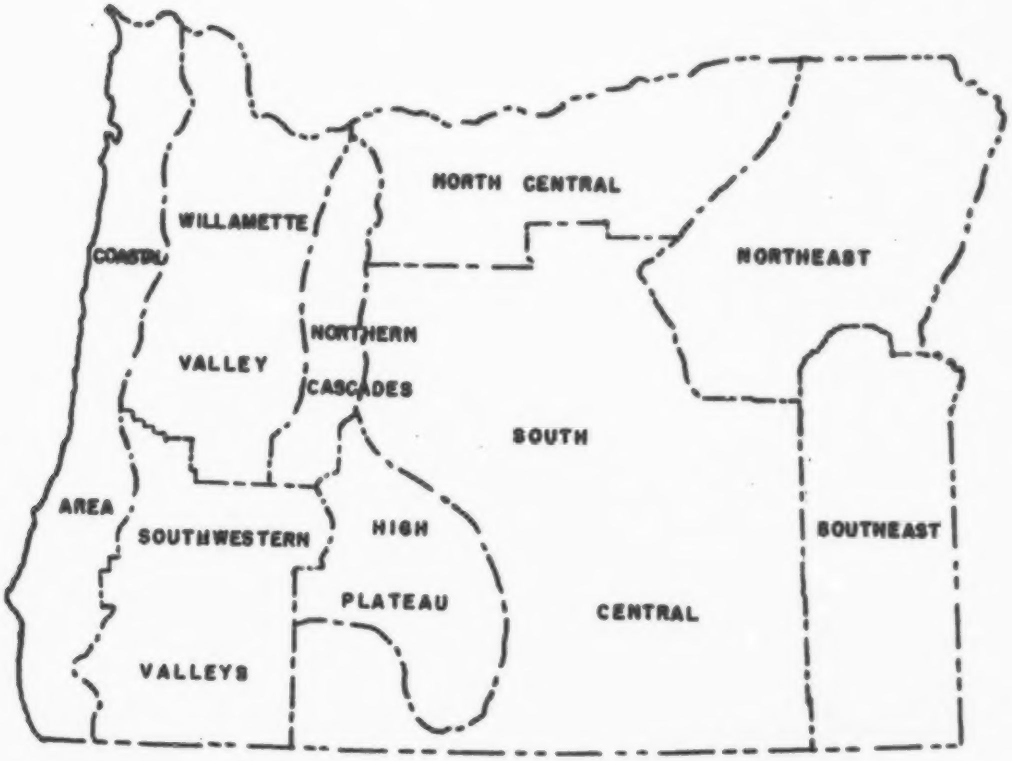
NORTH CENTRAL
WILLAMETTE
COASTAL
NORTHEAST
NORTHERN
VALLEY
CASCADES
SOUTH
AREA
SOUTHWESTERN
HIGH
SOUTHEAST
PLATEAU
CENTRAL
VALLEYS

Figure 1-A. Oregon Map with U.S. Weather Bureau Districts

Table 1A. Long-Term Mean Monthly Precipitation - Division Averages

MONTH	COASTAL	WILLAMETTE	SOUTHWESTERN VALLEY	NORTHERN CASCADES	HIGH PLATEAU	NORTH CENTRAL	SOUTH CENTRAL	NORTHEAST	SOUTHEAST
January	11.71	7.71	4.81	8.50	5.40	1.91	1.48	2.29	1.10
February	9.73	6.25	3.41	7.28	3.82	1.52	1.14	1.96	0.93
March	8.90	5.59	3.09	7.40	3.55	1.35	1.03	1.87	0.85
April	4.91	3.30	2.06	4.43	2.11	1.04	0.92	1.56	0.82
May	3.30	2.66	1.90	4.04	1.90	1.01	1.21	1.73	0.97
June	2.31	2.04	1.44	3.23	1.64	1.12	1.25	1.94	0.99
July	0.72	0.53	0.25	0.79	0.41	0.23	0.29	0.49	0.23
August	0.86	0.69	0.26	0.83	0.48	0.25	0.31	0.46	0.18
September	2.21	1.80	0.87	2.46	0.91	0.61	0.54	0.83	0.37
October	6.59	4.93	2.78	6.22	2.85	1.33	1.00	1.52	0.68
November	10.56	7.62	4.17	8.79	4.54	1.89	1.36	2.15	0.96
December	13.62	8.64	5.25	10.21	5.97	2.13	1.61	2.56	1.18
ANNUAL	75.42	51.76	30.29	64.17	33.58	14.39	12.14	19.36	9.26

Table 2A. Evaporation

MONTH	COASTAL	WILLAMETTE VALLEY	SOUTHWESTERN VALLEY	NORTHERN CASCADES	HIGH PLATEAU	NORTH CENTRAL	SOUTH CENTRAL	NORTH-EAST	SOUTH-EAST
January	NO INFORMATION	---	0.88	---	---	---	---	NO INFORMATION	---
February		---	1.12	---	---	---	---		---
March		---	2.40	---	---	---	---		---
April		2.99	3.86	---	---	4.59	4.68		4.85
May		4.27	4.12	3.16	3.50	5.36	7.13		7.68
June		5.88	6.16	6.63	9.05	9.37	9.40		9.88
July		8.01	8.52	7.63	9.15	10.68	11.55		11.80
August		6.89	7.11	6.16	7.11	9.67	9.46		9.84
September		4.17	4.76	2.66	4.11	6.79	5.97		6.22
October		2.52	1.97	0.51	3.53	2.85	3.11		3.07
November		---	0.67	---	---	---	---		---
December		---	0.51	---	---	---	---		---
ANNUAL		34.73	41.08	26.75	36.45	49.31	51.30		53.34

APPENDIX B- 1

PREDICTION OF AVERAGE AND DIURNAL TEMPERATURES IN WASTE WATER LAGOONS

by

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LAGOON TEMPERATURES

Introduction

Lagoon temperatures are important with respect to (a) production and propagation of algae, (b) chemical and metabolic reaction rates, (c) algal respiration, and (d) dissolved oxygen saturation values.

The optimum temperature for the production and propagation of algae varies from 18°C to 30°C for green algae and 35°C to 40°C for blue-green algae (12B, p. 56). Other research done in this field, however, reveals that temperatures of 8°C to 13°C do not interfere with the production of large algal crops and are not a hindrance to lagoon operation (5B, p. 26). This is also confirmed by the successful operation of waste water lagoons in areas such as the Dakotas, Canada, and the State of Alaska (1B, p. 342; 8B, p. 95; 13B, p. 1; 15B, p. 324), where freezing temperatures prevail throughout most of the winter months.

By Vant Hoff's Theory, metabolic reaction rates are increased from 2 to 3 times by every 10°C increase in temperature. Both aerobic and anaerobic waste stabilization reactions follow this relationship, with useful temperature limits being 3°C and 35°C. The lower limit is due to the retardation of bacterial and algal activity at temperatures approaching freezing, and the upper limit is the result of thermal inactivity of most species of algal (7B, p. 965).

Temperature affects the stabilization process mainly through its influence on the rate of BOD reaction, including algal respiration, and on the dissolved oxygen saturation value. Oxygen production by photosynthetic activity must also be considered. Laboratory tests have shown that with certain species of Chlorella, a rise of 10°C may accelerate the photosynthetic rate from 50 percent to more than 200 percent. A generally similar temperature effect has been found also for algae living under natural conditions (3B, p. 72).

Water temperature of lagoons may be expected to range from near 0°C in winter to more than 35°C at midsummer. Over this range the rate at which the ultimate carbonaceous BOD is satisfied changes widely. The following table, (Table 1B), indicates it takes 13 days at 5°C to accomplish what it takes only 4 days at 30°C.

Table 1B

Effect of Temperature on Rate of BOD Satisfaction

Temp. °C	Time in Days* for 90% BOD Satisfaction
5	13.1
10	10.4
15	8.3
20	6.7
25	5.3
30	4.2

* $K_1 = 0.15$ at 20°C Based on ultimate 1st stage BOD

$K = k_{20} (1.047)$

Prediction of Lagoon Temperatures in Oregon

Oregon is marked, climatically, by several distinct regions, ranging from the mild coastal climate to the often severe conditions encountered in the northeastern section of the state. These regions present different problems as far as oxidation lagoon temperature prediction is concerned.

Most methods of predicting pond temperatures are based on the Heat-Budget Method, which accounts for energy entering and leaving the body of water under consideration (2B; 10B; 14B). The method of prediction chosen for this paper is a modification of the Heat-Budget Method as described by Harback and Greene in an article entitled "A Method of Estimating Maximum Temperatures to be Expected in Ponds and Small Lakes" (6B). This method has been modified still further to make it applicable to waste water lagoons. A full description of the method and the computational techniques involved is included in the appendix.

Water temperature predictions by this method are based upon climatological data from the specific area under consideration. The meteorological information required is obtainable from U.S. Weather Bureau Stations of the first order. Of the ten first order weather stations in Oregon, eight were chosen to represent the different areas of the state. These stations are listed in Table 2B.

Table 2B

First Order Weather Stations in Oregon

Station	Location in State
Astoria	North Coast
Portland	Lower Willamette Valley
Medford	Southwestern Region
Burns	Eastern Region
Roseburg	Umpqua Valley
Pendleton	Northeastern Region
Eugene	Willamette Valley
Salem	Willamette Valley

The months of June, July, August, and September were selected as being critical with respect to high lagoon temperatures. Predictions of average and maximum lagoon temperatures expected during each of these months were carried out. Table 3B gives the results of the computations which were performed.

The accuracy and validity of these predicted lagoon temperatures can be verified only after several years of observations have been made. These predictions are simply an attempt at describing the potential thermal environment, with respect to oxidation lagoons, throughout the State of Oregon. It would be inadvisable to use these predictions unless they were used judiciously with a full understanding of their limitations and restrictions (see appendix).

Diurnal Variation of Lagoon Temperatures

Another problem inherent in the study of lagoon temperatures is that of diurnal fluctuations. Throughout the day various meteorological conditions impose their effects on a lagoon so as to change its temperature. If it were possible to describe these diurnal changes in temperature by some mathematical means, then it might also be possible to use this information in order to predict when these thermal changes occur.

A means of describing diurnal variations of a natural phenomenon is through the use of periodic regression analysis. Bliss states in the foreword of his pamphlet entitled "Periodic Regression in Biology and Climatology" (4B):

> Periodic phenomena in biology and climatology occur so widely that we tend either to adapt to them as unavoidable nuisances or are overimpressed by their day to day deviations. We can't 'see the forest for the trees.' If the variable occurs around the clock or

Table 3B

Predicted Lagoon Temperatures in Oregon

Station	Month	Average Temperature °F	Maximum Temperature °F
Astoria	June	59.5	78.5
	July	67.5	88.0
	Aug.	63.0	84.0
	Sept.	54.0	81.0
Portland	June	61.5	85.0
	July	69.0	94.0
	Aug.	66.0	88.0
	Sept.	56.0	81.0
Medford	June	73.0	100+
	July	82.5	100+
	Aug.	77.0	100+
	Sept.	65.0	95.0
Burns	June	68.5	95.0
	July	75.5	100.0
	Aug.	73.0	98.0
	Sept.	58.0	85.0
Roseburg	June	73.0	95.5
	July	78.0	100+
	Aug.	73.0	100.0
	Sept.	60.0	90.0
Pendleton	June	63.5	90.0
	July	71.0	95.0
	Aug.	68.5	93.0
	Sept.	55.0	82.0
Eugene	June	67.0	92.0
	July	73.0	100.0
	Aug.	66.5	91.5
	Sept.	59.0	85.0
Salem	June	65.0	90.0
	July	75.0	100+
	Aug.	67.5	92.0
	Sept.	57.0	86.0

> **through the year, but with systematically unequal magnitudes, its underlying pattern can often be expressed logically in relatively simple trigonometric terms. When this classical mathematical model is combined with an appropriate statistical analysis, we are better able to describe the periodic trend and to study deviations from its pattern . . .**

Two separate twelve-day periods were studied at the Oregon State University Experimental Lagoon using the methods outlined by Bliss. A two-pen recording thermograph was used to obtain both air and water temperatures for the periods from June 20, 1963, to July 1, 1963, and from August 9, 1963, to August 20, 1963. The lagoon temperature was taken at a depth of 1.7 feet which had been previously determined as the depth at which the average lagoon temperature usually is found. The air temperature was taken at a point where it would not be influenced by the lagoon's proximity.

By the use of periodic regression techniques (see appendix, this section) two sets of curves were obtained which describe the diurnal variation of air and water temperature for the two periods (see Figures 1-B and 2-B). These curves can be described in trigonometric terms.

$$Y = a_o + a_1 \cos (ct) + b_1 \sin (ct) + a_2 (\cos 2\, ct) +$$
$$b_2 \sin (2\, ct) + \ldots + a_n \cos (n\, ct) + b_n \sin (n\, ct)$$

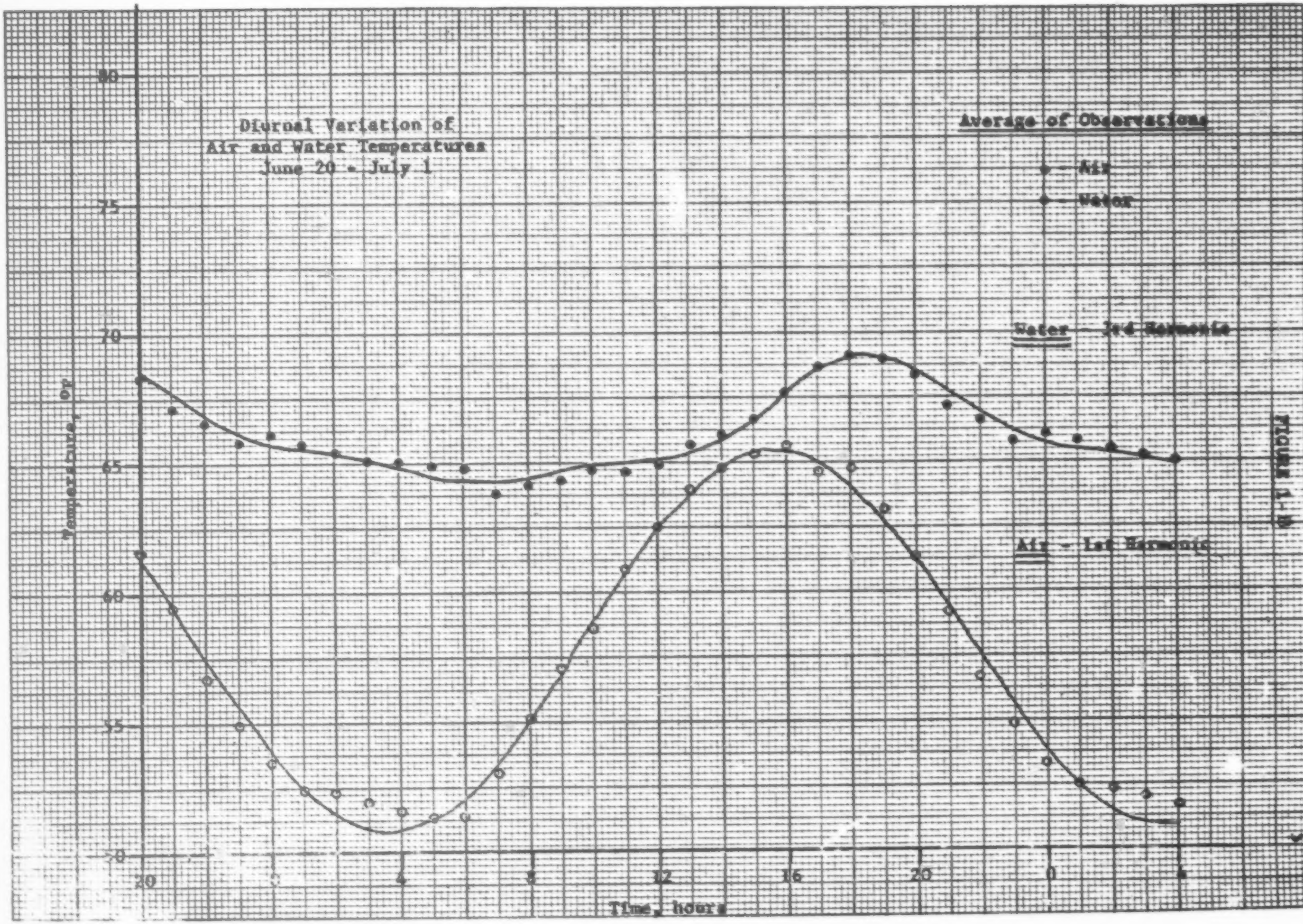
where,

Y = temperature
a_o = average diurnal temperature
$a_1, b_1, a_2, b_2, \ldots a_n, b_n$ = harmonic constants
c = one time period, in radians
t = time

This equation is discussed further in the appendix.

The problem of describing the diurnal variations in temperature is solved by using harmonic curves, as was done above. This analysis, however, does not eradicate the problem of predicting the magnitude or temporal circumstances of the changes. The problem of predicting diurnal changes in temperatures is made more difficult as the order of the harmonic which describes the curve increases. The number of the unknowns in the harmonic equation describing the diurnal fluctuation of temperature is equal to $n + 1$, where n is the order of the harmonic. Therefore, for a first order harmonic only three parameters of the equation are unknown, but for a third-order harmonic there are seven unknown parameters. This is noted further in the appendix.

FIGURE 1-B


Diurnal Variation of
Air and Water Temperatures
June 20 - July 1
Average of Observations
● - Air
● - Water
Water - 3rd Harmonic
Air - 1st Harmonic
Temperature, °F
80
75
70
65
60
55
50
Time, hours
20
0
4
8
12
16
20
0
4

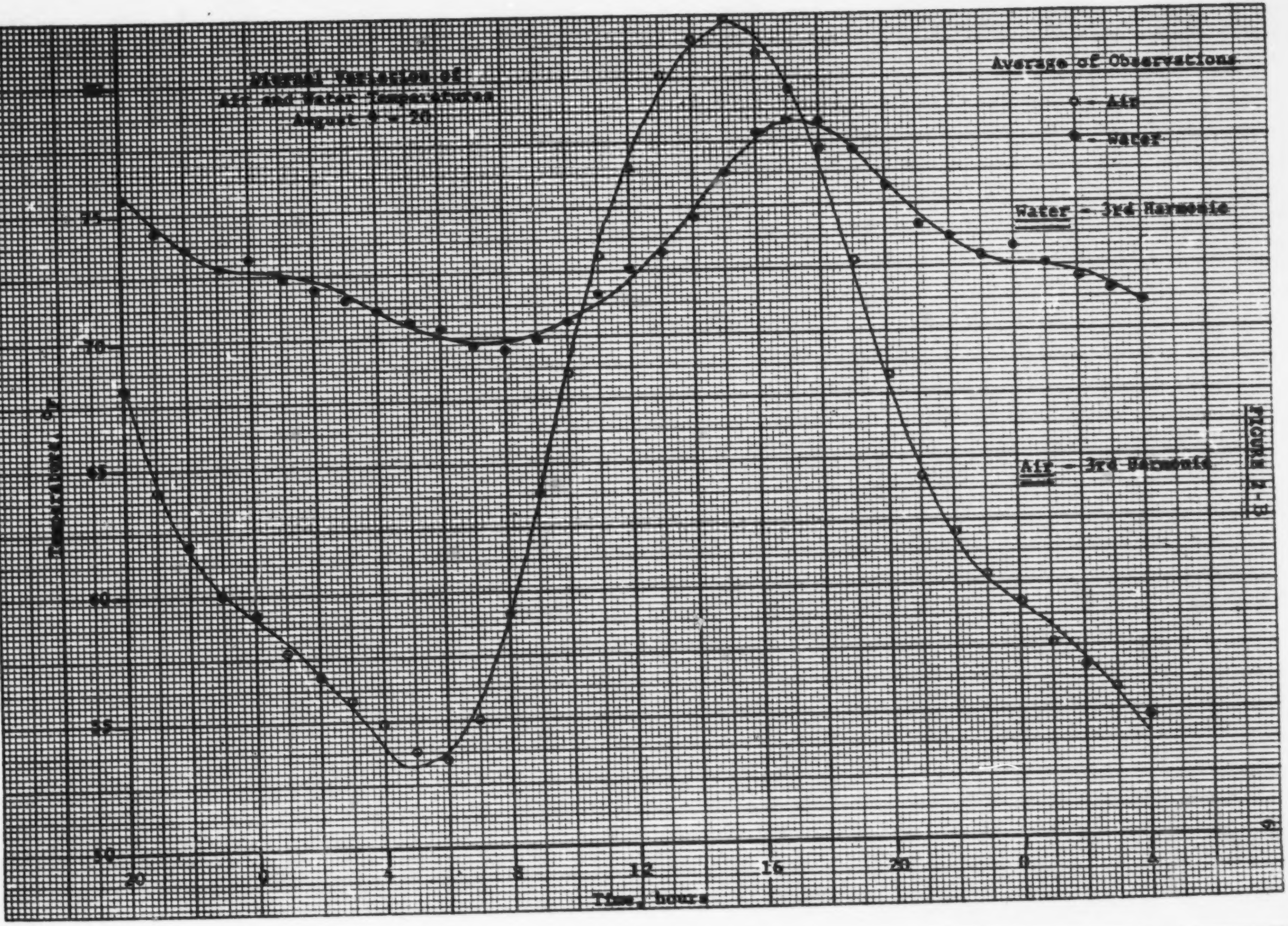

Diurnal Variation of
Air and Water Temperatures
August 4 - 20
Average of Observations
○ - Air
● - Water
Water - 3rd Harmonic
Air - 3rd Harmonic
Temperature °F
80
75
70
65
60
55
50
20
0
4
8
12
16
20
0
4
Time, hours
6

FIGURE 2-B

Conclusion

The necessity of predicting water temperatures has just recently come to the fore as a real engineering problem. The methods described above for prediction of monthly lagoon temperatures and for mathematically describing diurnal temperature fluctuations are merely steps in the direction of a solution to the over-all problem. More work must be done on the problem before one will be able to say, "This is the answer."

Research should be carried out to determine such things as:

1. The magnitude of biological heating in lagoons.
2. Physical characteristics of lagooned sewage (i.e.: specific heat, latent heat of vaporization, etc.)
3. Reflective characteristics of an algal moss.
4. Uniformity of heating in a lagoon.

Also, more statistical work should be carried out to evaluate the importance of regression analysis for predicting diurnal variations in temperature and to find a means for predicting the various harmonic constants.

As work continues, many facets of the problem not yet noted may be revealed. Even though the problem is complex, there may be a solution of a relatively simple nature dealing with factors unknown at the present time.

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APPENDIX

Prediction of Average and Diurnal Temperatures in Waste Water Lagoons Section

METHOD OF PREDICTING OXIDATION LAGOON TEMPERATURES

The method used for the lagoon temperature predictions presented previously in this report was a modification of a method presented by Harbeck and Greene (6B). Their method is an application of the Heat-Budget Method for ponds and small lakes.

The basic Heat-Budget equation accounts for the energy which enters or leaves the body of water under consideration. The following equation includes the routes of energy transport which must be considered.

$$Q_t = Q_s - Q_b \pm Q_e \pm Q_h \pm Q_a$$

where,

Q_t = net gain or loss of energy
Q_s = incoming solar radiation
Q_b = back radiation
Q_e = energy lost by evaporation (or gained by condensation)
Q_h = energy lost or gained by conduction
Q_a = advected energy

Certain assumptions and changes were made by Harbeck and Greene with respect to this basic equation:

1. The change in heat storage in the body of water is zero. This assumption is valid, since small ponds would reach equilibrium conditions.
2. Back radiation from the water surface is proportional to the fourth power of the absolute temperature of the water surface. For ease of computation, the exact relationship was replaced by a linear approximation with a maximum error of one percent in the range of water surface temperatures normally found in the summer.
3. The outflow temperature equals the water surface temperature.

With these changes made, the equation derived by Harbeck and Greene takes the following form (6B, p. 496).

$$Q - 3\,Tw - 1.3\,u\,(ew - ea) - 0.4\,(Tw - Ta) + 17\,I/A\,(Ti - Tw) = 216$$

where,

Q = incoming solar radiation in langleys (calories per square centimeter) per day

T_w = water surface temperature in $^{\circ}F$

u = wind speed in miles per hour

e_w = vapor pressure of saturated air at the temperature of the water surface in millibars

e_a = vapor pressure of the air in millibars

T_a = temperature of the air in $^{\circ}F$

I = inflow in cubic feet per second

A = surface area of the pond in acres

T_i = temperature of the inflow in $^{\circ}F$

Further changes were made in this equation to make it compatible to the specific problem of predicting waste water lagoon temperatures. One of these changes was to use the average temperature of the lagoon with respect to depth instead of the surface temperature. This was done because observations made at the Oregon State University Experimental Oxidation Lagoon showed that the surface temperature was at times as many as 5°F higher than the average temperature in the lagoon. The average difference between surface temperature and average temperature is, however, only about 2°F. By changing the "T_w" term from surface to average water temperature, a slight bias was introduced into the equation which tended to give predicted lagoon temperatures which are slightly high. Thus this change makes the method somewhat conservative.

The following assumptions were made to account for the advected energy term, $17\ I/A\ (T_t - T_w)$.

1. lagoon loaded at 20 lb BOD/acre/day

2. 1/6 lb BOD/person/day

3. sewage flow = 200 gpcd

Solving for I gives:

$$I = \frac{(20\ \text{lb BOD/acre/day})(200\ \text{gpcd})}{(1/6\ \text{lb BOD/person/day})} = 24{,}000\ \text{gal/acre/day}$$

Converting gal/day to cfs gives:

$$I = (0.024\ \text{mgd/acre})(1.547\ \text{cfs/mgd}) = 0.0371\ \text{cfs/acre}$$

Assuming A = 1 acre gives:

$I/A = 0.0371$

Therefore:

$17\ I/A = 0.631$

The temperature of the inflow was assumed to equal 50°F.

After these modifications, the equation in its final form is:

$$Q = 3\ T_w - 1.3\ u\ (e_w - e_a) - 0.4\ u\ (t_w - t_a) + 0.631\ (50 - T_w) = 216$$

where,

Q, u e_w, t_a = previously defined

T_w = lagoon temperature (averaged with respect to depth)

This equation is solved by estimating a T_w for a given set of meteorological data. Estimation of T_w is done on a trial and error basis until the left side of the equation equals 216 ± 5.

The use of reliable climatological data is imperative if the temperature predictions made by this method are to be of significant value. In predicting monthly average lagoon temperatures for the eight selected areas of the State of Oregon, the necessary meteorological information was obtained in the following manner.

1. $\underline{T_a}$ The average air temperature for each of the four selected months was taken from the climatological standard normals (1931 - 1960) for each station.

2. u* The average wind speed was taken from the local climatological data for the year 1962.

3. relative humidity* The average relative humidity was taken as the average of the four readings at 4 AM, 10 AM, 4 PM, and 10 PM for the year 1962. For stations which have relative humidity readings only at 10 AM and 4 PM the average relative humidity was obtained by multiplying the average of the two readings by 1.3. Relative humidity is required for the computation of e_a as will be shown later.

---

* Since long-term averages of wind and relative humidity were not available, the best expedient was to use the 1962 data. The use of this data as opposed to long-term data should not bias the results too much to either one side or the other.

4. Q The average solar radiation was taken from maps prepared by Sternes (11B). These maps give average daily solar radiation received in Oregon on a horizontal surface at the ground in langleys per day.

In computing monthly maximum lagoon temperatures, the following changes were made in the data.

1. T_a The air temperature was taken as the 1962 high for the particular month being considered. All maximum temperatures over 100°F were used as 100°F in the computations.

2. u The wind speed was taken as one-half the 1962 average.

3. relative humidity The same relative humidity that was used for computing average monthly temperature was used.

4. Q The solar radiation figure used was equal to 100 ly/day plus that used in computing average monthly temperatures.

The vapor pressure terms, e_a and e_w, are derived from a table of vapor pressure in millibars at various temperatures (6B, p. 496). The value of e_a is computed by multiplying the vapor pressure for T_a by the relative humidity. The value for e_w is the vapor pressure obtained from the table for T_w.

The following 3 pages show a trial and error solution for the Pendleton station in September. Also included is the local climatological data sheet for Pendleton and Sterne's radiation map. These will help facilitate matters if it is desired to check the method of data extraction outlined previously.

Lagoon Temperature Predictions

Weather Station: Pendleton
Month: September
Average or Maximum: Average
Trial Number: 1
Data & Computation:

Q = 450 ly/ day
u = 8.6 mph
relative humidity - 40.3%
$T_a = 64.2^{\circ}F$
$e_a = 5.8$ mb
assumed $T_w = 62^{\circ}F$
$e_w = 19.0$ mb

$450 - 3(62) - 1.3(8.6)(19.0-5.8) - 0.4(8.6)(62-64.2) + 0.631(50-62) \overset{?}{=} 216$

$450 - 186 - 147.6 - (-7.6) + (-7.6) \overset{?}{=} 216$

$116.4 \neq 216$

OK ______, T_w = ______ °F
NG __x__, try T_w = __60__ °F for next trial

Weather Station: Pendleton
Month: September
Average or Maximum: Average
Trial Number: 2
Data & Computation:

Q = 450 ly/ day
u = 8.6 mph
relative humidity = 40.3%
$T_a = 64.2^{\circ}F$
$e_a = 5.8$ mb
assumed $T_w = 60^{\circ}F$
$e_w = 17.7$ mb

$450 - 3(60) - 1.3(8.6)(17.7-5.8) - 0.4(8.6)(60-64.2) + 0.631(50-60) \overset{?}{=} 216$

$450 - 180 - 133 - (-14.4) + (-6.3) \overset{?}{=} 216$

$145.1 \neq 216$

OK ______, T_w = ______ °F
NG __x__, try T_w __55__ °F for next trial

Weather Station: Pendleton
Month: September
Average or Maximum: Average
Trial Number: 3
Data & Computation:

Q = 450 ly/day
u = 8.6 mph
relative humidity = 40.3%
T_a = 64.2°F
e_a = 5.8 mb
assumed T_w = 55°F
e_w = 14.8 mb

$$450 - 3(55) - 1.3(8.6)(14.8-5.8) - 0.4(8.6)(55-64.2) + 0.631(50-55) \overset{?}{=} 216$$

$$450 - 165 - 100.6 - (-31.6) + (-3.2) \overset{?}{=} 216$$

$$212.8 \cong 216$$

OK __x__, T_w = __55__ °F
NG ______, try T_w = ______ °F for next trial

Weather Station: Pendleton
Month: September
Average or Maximum: Maximum
Trial Number: 1
Data & Computation:

Q = 550 ly/day
u = 4.3 mph
relative humidity = 40.3%
T_a = 93°F
e_a = 21.3 mb
assumed T_w = 85°F
e_w = 45.2 mb

$$550 - 3(85) - 1.3(4.3)(45.2-21.3) - 0.4(4.3)(85-93) + 0.631(50-85) \overset{?}{=} 216$$

$$550 - 255 - 133.6 - (-13.8) + (-22.1) \overset{?}{=} 216$$

$$153.1 \neq 216$$

OK ______, T_w = ______ °F
NG NG __x__, try T_w = __80__ °F for next trial

Weather Station: Pendleton
Month: September
Average or Maximum: Maximum
Trial Number: 2
Data & Computation:

$Q = 550$ ly/ day
$u = 4.3$ mph
relative humidity = 40.3%
$T_a = 93^{o}F$
$e_a = 21.3$ mb
assumed $T_w = 80^{o}F$
$e_w = 35.0$ mb

$550 - 3(80) - 1.3(4.3)(35-21.3) - 0.4(4.3)(80-93) + 0.631(50-80) \overset{?}{=} 216$

$550 - 240 - 76.6 - (-22.4) + (-18.9) \overset{?}{=} 216$

$236.9 \neq 216$

OK ______, T_w = ______ ^{o}F
NG __x__, try T_w = __82__ ^{o}F for next trial

Weather Station: Pendleton
Month: September
Average or Maximum: Maximum
Trial Number: 3
Data & Computation:

$Q = 550$ ly/ day
$u = 4.3$ mph
relative humidity = 40.3%
$T_a = 93^{o}F$
$e_a = 21.3$ mb
assumed $T_w = 82^{o}F$
$e_w = 37.3$ mb

$550 - 3(82) - 1.3(4.3)(37.3-21.3) - 0.4(4.3)(82-93) + 0.631(50-82) \overset{?}{=} 216$

$550 - 246 - 89.4 - (-18.9) + (-20.2) \overset{?}{=} 216$

$213.3 \cong 216$

OK __x__, T_w = __82__ ^{o}F
NG ______, try T_w ______ ^{o}F for next trial

U. S. DEPARTMENT OF COMMERCE
WEATHER BUREAU

LOCAL CLIMATOLOGICAL DATA

1962

PENDLETON, OREGON

ANNUAL SUMMARY

[illegible]

CLIMATOLOGICAL STANDARD NORMALS (1931-1960)

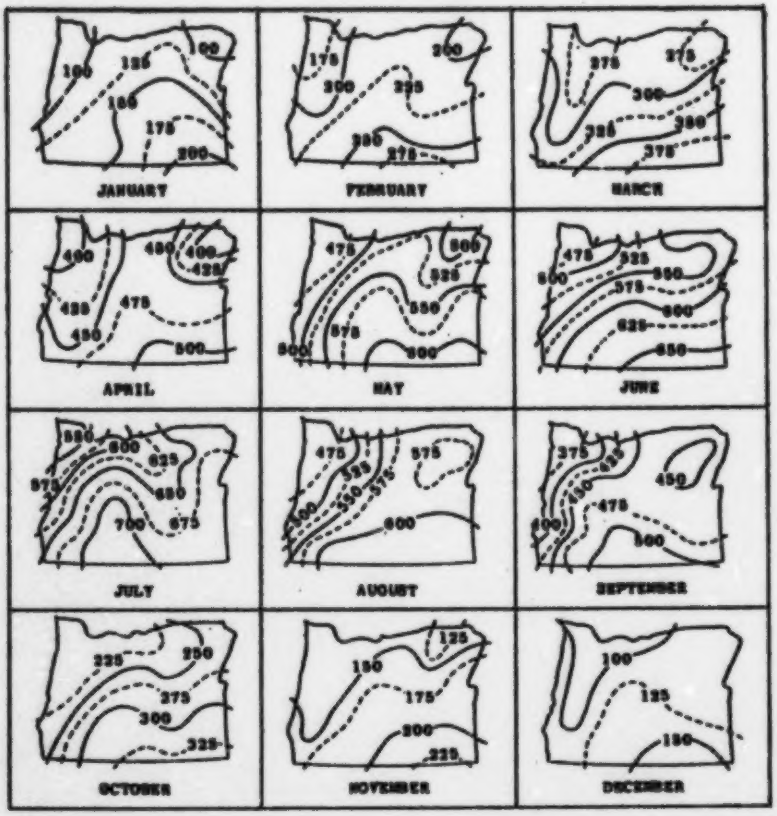
[illegible]	January	February	March	April	May	June	July	August	September	October	November	December	Annual
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

REFERENCE NOTES AND INSTRUMENT RELOCATIONS

[illegible]

[illegible]

Average Daily Solar Radiation
Received in Oregon on a Horizontal
Surface at the Ground in Langleys per Day
(11B, Sternes)


JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

Limitations and Restrictions

The following statements should be well regarded before one uses the modified method of Harbeck and Greene to predict oxidation lagoon temperatures.

1. No attempt was made to modify the method to account for the difference between natural water and sewage as found in lagoons.
2. The method does not account for heated discharges into a lagoon.
3. The method tends to predict somewhat high in many instances.
4. The accuracy of the predictions are based upon the accuracy of the meteorological data which is available.
5. The method is applicable only during the summer months.

Periodic Regression Techniques Used in Describing the Diurnal Fluctuation of Air and Water Temperatures

A comprehensive discussion of periodic regression techniques would be too lengthy to include in this report. For such a discussion, the reader is urged to read the article by Bliss (4B).

Basically, the techniques of periodic regression make it possible to fit cyclical variables (i.e.: diurnal variation in temperature) to a defined mathematical curve. Fourier Series or harmonics make it possible to describe the variations in trigonometric terms.

$$Y = a_o + a_1 \cos(ct) + b_1 \sin(ct) + a_2 \cos(2ct) + b_2 \sin(2ct) + \ldots$$
$$\ldots a_n \cos(nct) + b_n \sin(nct)$$

where,

Y = temperature
a_o = average diurnal temperature
$a_1, b_1, a_2, b_2 \ldots, a_n, b_n$ = harmonic constants
c = one time period, in radians
t = time

This equation can be written in a different form as will be shown later.

By statistical analysis it is possible to determine which terms of the Fourier Series are significant and which terms should not be included in the final equation.

The statistical technique used by Bliss to determine the significance of the harmonic terms is the analysis of variance or AOV (4B, p. 12). When applying Bliss's techniques to the specific problem at hand, a less complicated AOV was employed.

Table 1B on the following page shows the AOV which was used. The reader who is unfamiliar with statistics is referred to Li's test "Introduction to Statistical Inference" (9B) or any other good statistics text.

In conducting the statistical analysis on the significance of the harmonic terms, the following hypothesis was tested.

Hyp.: $\alpha_n = \beta_n = 0$

where,

a_n is an unbiased estimate of α_n

b_n is an unbiased estimate of β_n

The F-test was used at a level of significance of 5 percent. When the value of F was low enough for the specific hypothesis to be accepted, then that term in the Fourier Series was not significant. Table 2B on page B-25 shows the various F values for the four AOV's which were run.

As Table 2B shows, all the curves tested were third order harmonics except for the air curve of June 20 - July 1, which was a first order harmonic.

Some preliminary trigonometric work was carried out to try and make the equations more manageable for purposes of predicting. The basic equation (see page B-22) can be changed as shown below for both a first and third order harmonic equation.

Table 1B

ITEM	DF	SS	MS	F
Replicate	$f - 1$	$\Sigma T_r{}^2 / k - G^2 / fk$		
(a_1, b_1)	2	$[(\Sigma u_1 T_t)^2 + (\Sigma v_1 T_t)^2] / (1/2\ fk)$	SS/DF	MS/Residual MS
(a_2, b_2)	2	$[(\Sigma u_2 T_t)^2 + (\Sigma v_2 T_t)^2]\ (1/2\ fk)$		
(a_n, b_n)	2	$[(\Sigma u_n T_t)^2 + (\Sigma v_n T_t)^2]\ (1/2\ fk)$		
Residual	by diff.	by difference		
Total	$fk - 1$	$\Sigma y^2 - G^2 / fk$	---	---

In the analysis carried out in this report, $f = 12$ and $k = 24$, where f = number of days and k = number of hours per day. For a complete explanation about the terms in Table 1B, the reader is referred to Bliss (4B, p. 4-16).

Table 2B

Period & F (5%)	Hypothesis	F	Conclusion
June 20 - July 1 (water)	$\alpha_1 = \beta_1 = 0$	492.0	reject
	$\alpha_2 = \beta_2 = 0$	49.5	reject
$F^{2}_{268}(5\%) \approx 3.0$	$\alpha_3 = \beta_3 = 0$	20.0	reject
	$\alpha_4 = \beta_4 = 0$	2.5	accept
June 20 - July 1 (air)	$\alpha_1 = \beta_1 = 0$	667.8	reject
$F^{2}_{272}(5\%) \approx 3.0$	$\alpha_2 = \beta_2 = 0$	0.9	accept
August 9 - 20 (water)	$\alpha_1 = \beta_1 = 0$	585.4	reject
$F^{2}_{268}(5\%) \approx 3.0$	$\alpha_2 = \beta_2 = 0$	60.3	reject
	$\alpha_3 = \beta_3 = 0$	9.1	reject
	$\alpha_4 = \beta_4 = 0$	2.6	accept
August 9 - 20 (air)	$\alpha_1 = \beta_1 = 0$	1,218.8	reject
	$\alpha_2 = \beta_2 = 0$	48.8	reject
$F^{2}_{268}(5\%) \approx 3.0$	$\alpha_3 = \beta_3 = 0$	5.1	reject
	$\alpha_4 = \beta_4 = 0$	0.03	accept

First Order Harmonic

$$Y = a_o + a_1 \cos(ct) + b_1 \sin(ct)$$

The term "c" is equal to the number of radians in one complete cycle divided by the number of time units in that cycle. Therefore,

$$c = 2\pi / 24 = 0.2618$$

Substituting "c" into the basic equation gives:

$$Y = a_o + a_1 \cos(0.2618t) + b_1 \sin(0.2618t)$$

where,

$$a_o = G / fk$$

$$a_1 = \frac{\Sigma(u_1 T_t)}{1/2\ fk}$$

$$b_1 = \frac{\Sigma(v_1 T_t)}{1/2\ fk}$$

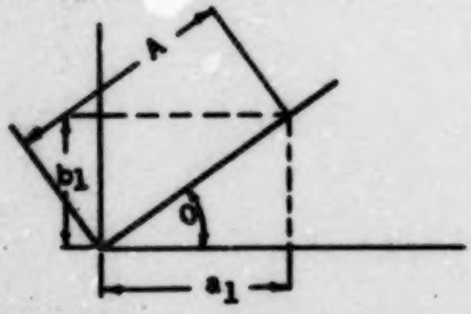
t = time

Y = temperature

(Note: These terms are discussed in detail by Bliss.)

By trigonometric manipulation, the equation can be simplified;

$A = \sqrt{a_1{}^2 + b_1{}^2}$ and $\theta = \tan^{-1}(b_1 / a_1)$ as shown below.



where,

θ = the phase angle of maximum response

A = the semi-amplitude

From this drawing it is evident that: $a_1 = A \cos\theta$ and $b_1 = A \sin\theta$

By substituting these terms for a_1 and b_1 the equation becomes:

$$Y = a_o + A \cos\theta \cos(0.2618t) + A \sin\theta \sin(0.2618t)$$

$$Y = a_o + A\,[\cos\theta \cos(0.2618t) + \sin\theta \sin(0.2618t)]$$

By using the trigonometric identity,

$$\cos(a - \theta) = \cos a \cos\theta + \sin a \sin\theta$$

The equation, upon substitution, becomes: *

$$\underline{Y = a_o + A \cos(0.2618t - \theta)}$$

This form of the equation permits faster computation, and therefore greater ease of solution.

Third Order Harmonic

$$Y = a_o + a_1\cos(ct) + b_1\sin(ct) + a_2\cos(2ct) + b_2\sin(2ct) + a_3\cos(3ct) + b_3\sin(3ct)$$

By using the same reasoning as outlined above for the first order harmonic, the equation becomes:

$$\underline{Y = a_o + A \cos(0.2618t - \theta) + A' \cos(0.2618t - \theta') + A'' \cos(0.2618t - \theta'')}$$

where,

a_o, Y, t = previously defined

$A = \sqrt{a_1^2 + b_1^2}$ = semi-amplitude of 1st harmonic

$A' = \sqrt{a_2^2 + b_2^2}$ = semi-amplitude of 2nd harmonic

$A'' = \sqrt{a_3^2 + b_3^2}$ = semi-amplitude of 3rd harmonic

$\theta = \tan^{-1}(b_1/a_1)$ = phase angle of maximum response of 1st harmonic

$\theta' = \tan^{-1}(b_2/a_2)$ = phase angle of maximum response of 2nd harmonic

$\theta'' = \tan^{-1}(b_3/a_3)$ = phase angle of maximum response of 3rd harmonic

As was explained in the body of this report, the number of unknowns increases with each step up in the Fourier Series. One can easily see, by looking at the list of variables below the preceding equation, that any method of prediction of temperature by periodic regression would have to include some method of simplification of the harmonic relationships. Since no such method is included in this report, further mathematical and statistical investigations are necessary if periodic regression techniques in predicting lagoon temperatures are to be fully exploited.

APPENDIX C - 1

ANALYSIS FOR SLUDGE ACCUMULATION AND OXYGEN DEMAND IN OXIDATION LAGOONS

by

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Introduction

One of the factors having a marked effect upon waste water lagoons is the accumulated sludge deposits. These effect the oxygen resources of the lagoon as well as other operating parameters. The oxygen demand of this material is a function of several items, such as temperature variations, movement of overlying water, time of accumulation, oxidation rate, etc. An evaluation of the interrelation of all of these factors is of necessity, a complex undertaking. In this section, an attempt has been made to modify and apply the works of others to obtain a reasonable estimate of yearly variation in oxygen demand and sludge accumulation.

The most important single piece of data required in an evaluation of this type is an accurate estimate of the sludge oxidation rate. This has been denoted by Streeter (1C) as K' in the natural log system and 2.3 k' in the base 10 logarithmic system, where $k' = .434\ K'$. The oxidation of the organic sludge deposits in a lagoon may take place under a range of conditions from completely anaerobic to almost entirely aerobic. Fair and Moore (2C) report k' values ranging from 0.0044 under anaerobic conditions to 0.10 for aerobic conditions, both values being measured at 25°C. Streeter proposed that a value of $k' = 0.03$ at 25°C be used for the oxidation rate of sludge or sediments in flowing streams. This represents a compromise between the two extreme conditions.

The above determinations of k' were made for flowing streams, in which the decomposition products of the sludge deposit were removed from the liquid-solid interface and a concentration gradient was maintained such that the upward diffusion of the decomposition products is facilitated. In order to apply similar k' rates to oxidation lagoons, it was assumed that the lagoon was completely mixed. This assumption was based upon the observation that the combination of wind-generated currents and inflow provide essentially complete mixing.

Another factor to be considered in determining an oxidation rate is the state of the sludge deposit as regards aerobic or anaerobic conditions. In a lagoon under normal loading conditions, algal photosynthesis produces dissolved oxygen concentrations near or above saturation during the daylight hours. If complete mixing occurs, the surface of the deposit and possibly a short distance into the deposit are exposed to essentially aerobic conditions. During the night hours, algal respiration plus waste demand reduces the oxygen concentration to very low levels. Under these conditions it may be assumed that the entire sludge deposit is anaerobic. Based on these considerations, it would appear that for oxidation ponds Streeter's k' value of 0.03 would approximate a maximum oxidation rate and Moore's value of 0.0044 a minimum. Therefore, for this analysis it will be assumed that an average k' rate for lagoon sludge deposits is k' = 0.01 at 25°C.

The value of 2.3 k' represents the percentage of BOD accumulated at the end of the previous day which will be oxidized or utilized by the organisms in the deposit. Velz (3C), in his study of the significance of organic sludge deposits, has utilized the rate proposed by Streeter and has obtained very close correlation between predicted and actual effects of sludge deposits. The remainder of the report involves application of a method similar to that used by Velz to develop long term trends in sludge accumulation and oxygen demand at the Oregon State University Experimental Lagoon.

Analysis

Variations in the oxidation rate will result in changes in both sludge accumulation and oxygen. Since this coefficient describes the activity of a biological community, it is temperature sensitive and follows van t'Hoff's law; an increase in temperature brings about a corresponding increase in the oxidation rate. In order to develop the trends indicated above, therefore, the first step in the analysis is development of a yearly temperature profile for the lagoon.

The first assumption made was that sludge temperature equalled water temperature which is considered a fairly close approximation of actual conditions. For the purpose of this study, a water temperature profile should indicate average water temperature for each day in the year. Sufficient data were not available to develop a profile of this type. Instead, an attempt was made to determine average monthly temperatures. Data taken at the OSU lagoon from April 1960 through January 1962 were used to obtain an average for the months of October through April. But because OSU lagoon data were not sufficient for determining average summer temperatures, May through September average temperatures were predicted using a Heat-Budget method based upon meteorological data. This method of temperature prediction was developed by Harbeck and Greene and modified for lagoon temperatures by Tichenor (4C) as described later under "Temperature Studies." The resulting average monthly temperatures are listed in Table 1C.

Curves of best fit through the temperatures at midpoints of the respective months are shown in Figures 1C and 2C. For the time scale on this plot it was assumed that each month contained 30 days. Each month was further divided into six 5-day periods and the temperature at the midpoint of the period read from the curve. It was assumed that for any 5-day period the temperature at the midpoint was the average water temperature for each of the days in the period. These temperatures were tabulated and, using k' = 0.01 at 25°C as a basis, k' values for the various temperatures were determined using the standard temperature conversion formula (4C). The tabulation of temperatures and corresponding k' values follows at the end of this section.

Table 1C

Estimated Average Lagoon Temperature

Month	Average T-°F	Average T-°C
January	46.8	8.2
February	49.7	9.8
March	53.4	11.9
April	58.7	14.3
May	61.5	16.4
June	65.0	18.3
July	75.0	23.9
August	67.5	19.7
September	57.0	13.9
October	54.9	12.7
November	46.3	7.9
December	43.1	6.2

For this study a constant loading of 21 lbs/acre/day of 5-day 20°C BOD is assumed. One-third of the influent BOD was taken to be settleable, an average proposed by Fair and Geyer (5C). The result is that every day 7 lbs/acre of BOD is added to the sludge deposit, and 14 lbs/acre goes to the liquid phase.

In order to calculate the daily demand and change in accumulation using the above information, it is necessary to have a starting sludge accumulation. The time base of Figure 1C runs from July to July, so a starting value was obtained by assuming that the average temperature for the preceding June had been in effect long enough for the equilibrium concentration for the temperature to be reached. This is the concentration such that for a given k' rate, in this case .0075, the amount of oxygen utilized by the sludge just equals the amount of BOD added daily to the deposit. In this manner a starting concentration of 406 lbs of BOD/acre was obtained.

Calculation of the actual changes in accumulation and demand were then made. For the first 5-day period in July, 2.3 k' = 1.95. This means that for the first day in the period, 406 x 1.95 = 7.91 lbs BOD/acre were used. If it were assumed that the 7.0 lbs BOD/acre added every day was added as a slug at the end of each day, then the net change in lbs of BOD/acre equaled 7.0-7.9 = -0.9 lbs. Adding this to 406 gives a value of 405.1 lbs BOD/acre as a concentration at the beginning of the second day. The process was then repeated for every day in the year changing values of 2.3 k' every new 5-day period.

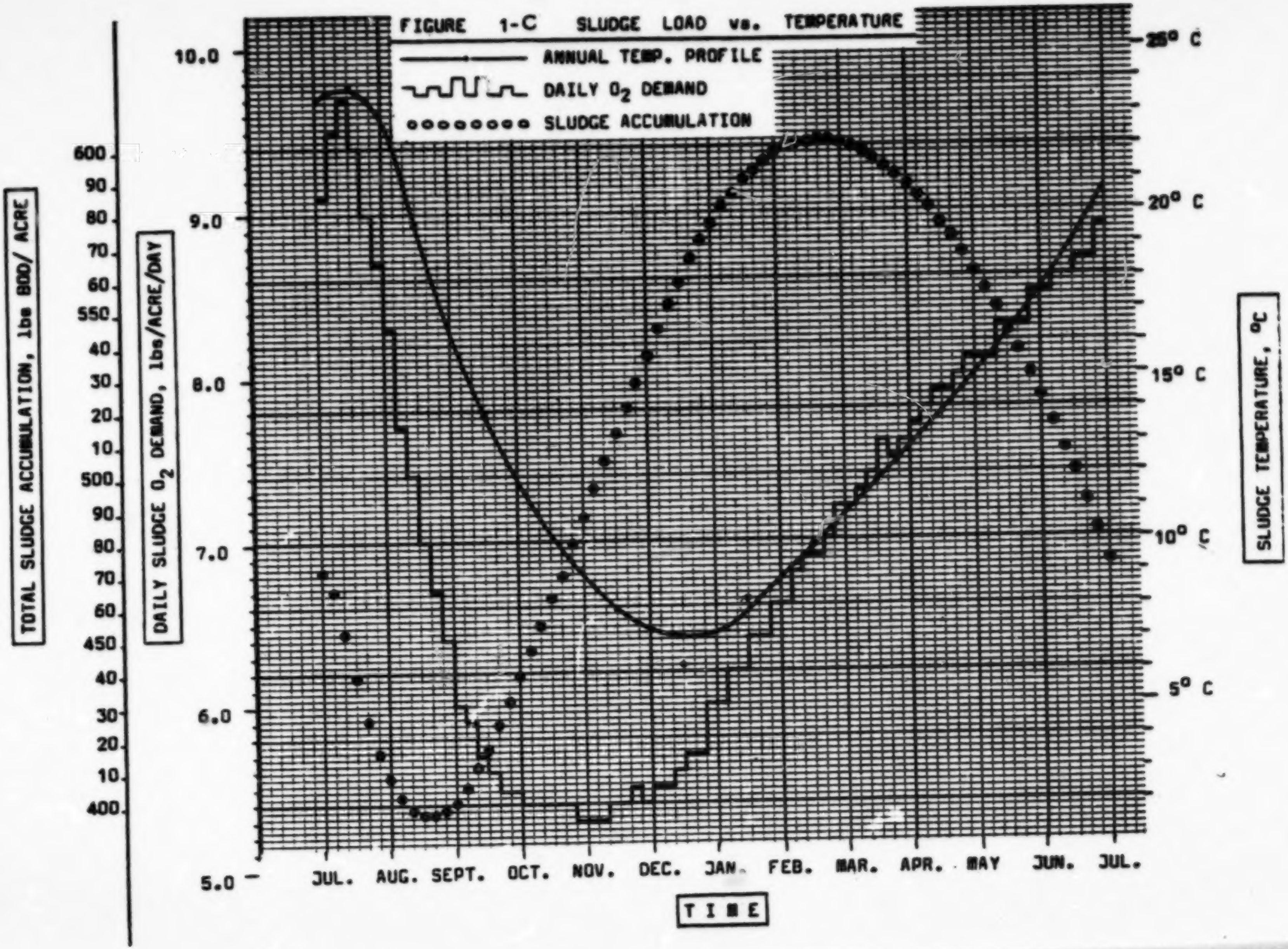
FIGURE 1-C SLUDGE LOAD vs. TEMPERATURE

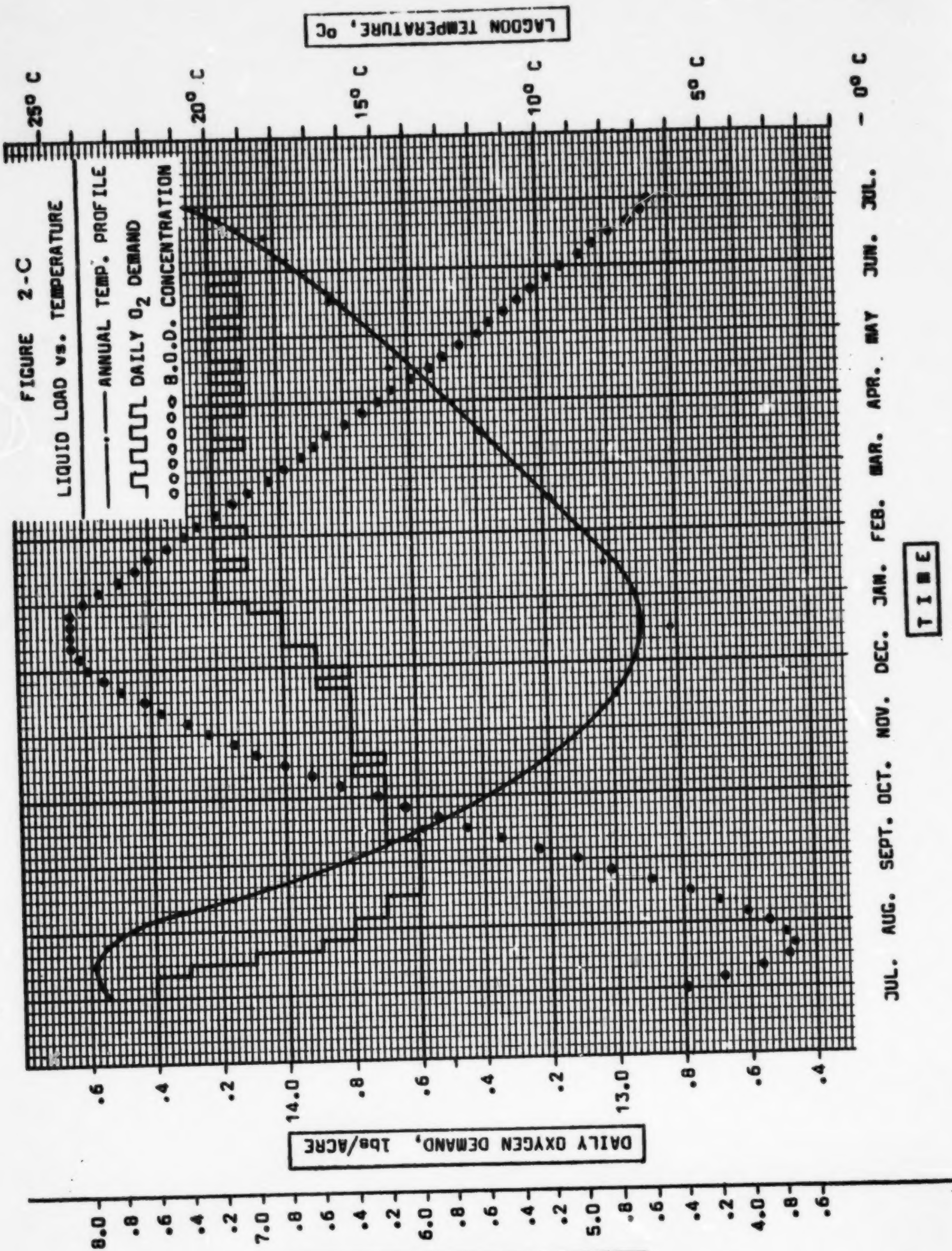

FIGURE 2-C

LIQUID LOAD vs. TEMPERATURE

When the calculations were carried through an entire year, the final sludge accumulation was determined to be 472.5 lbs BOD/acre. Since this was considerably higher than the starting value of 406 lbs/acre, a second run of calculations were carried out starting with the value obtained at the end of the first year. The final value for this run was 472.9 lbs BOD/acre, which compared favorably with the initial value (472.5). The results of these calculations are shown in tabular form at the end of this section and graphically on Figure 1C.

To complete the analysis, a similar set of calculations were carried out for the liquid phase. An average value of $k_1 = 0.39$ at 20°C was used. A starting point was determined by using the average k_1 value for June and computing the equilibrium concentration. This was determined to be 38 lbs BOD/acre. Results of calculations are shown in Figure 2C and the appendix.

As a final step, a curve was drawn which shows the yearly variation in daily demand of sludge plus liquid phase. This is indicated by Figure 3C.

Discussion

In this analysis of the variation in sludge accumulation and oxygen demand, a great many assumptions were made. Some were made because of data limitations while others were made for the purpose of simplifying calculations. If these are recognized and accounted for, however, it is believed that some interesting conclusions can be drawn.

An examination of Figure 1C shows that the curve for sludge accumulation is essentially a mirror image of the temperature profile, lags the temperature curve by approximately one month. This is due to the low oxidation rate for sludge. The peak daily demand in this case was reached about the middle of July. This would not necessarily be true for a different location for each area produces its own unique temperature profile. High sludge concentrations appeared in February, March, and April during which time the temperature profile shows a gradual, smooth increase. It should be remembered, however, that this curve was plotted from average monthly temperatures while in most areas, this is a period of highly unstable climatic conditions, and significant deviations from the average are the rule, rather than the exception. A sudden hot spell during March, for instance, might appreciably increase the water temperature in a short period of time. With a large accumulation of sludge, the daily oxygen demand of the sludge could increase to such an extent that the total oxygen demand, sludge plus liquid phase, exceeds the supply rate and the lagoon could then assume an anaerobic condition with its inherent problems.

Figure 2C shows that for the liquid phase the concentration curve of BOD is almost an exact mirror image of the temperature profile. This is because

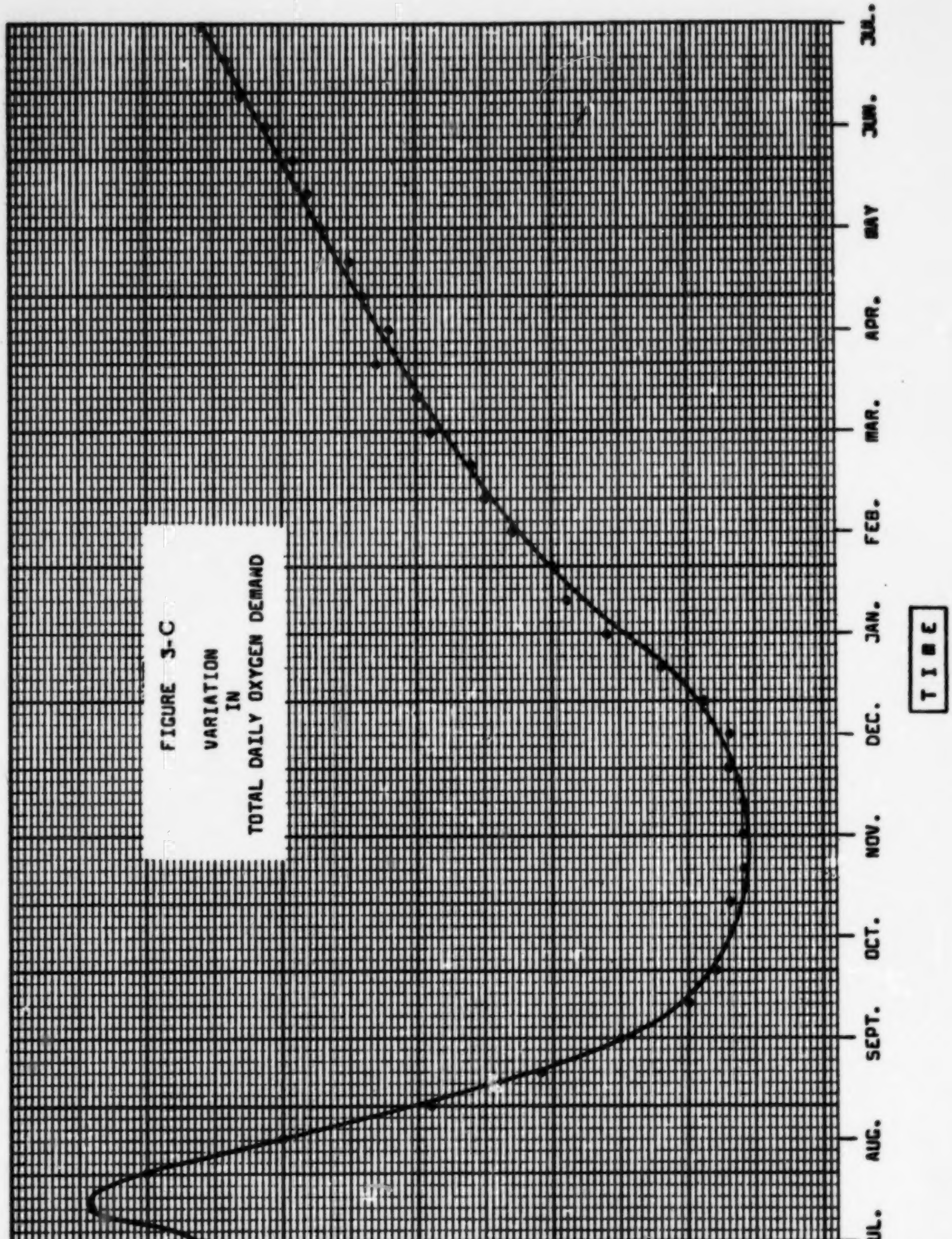

FIGURE 3-C

VARIATION

IN

TOTAL DAILY OXYGEN DEMAND

there is surprisingly little variation in the daily oxygen demand. The difference between maximum and minimum amounting to only 0.8 lb/acre.

In this analysis one major requirement was noted, that is, the need for adequate temperature data for sludge and water. If daily sludge and water temperatures were available for a long period of time and for locations experiencing a wide range of climatic conditions, an analysis of this type might indicate the reasons for some of the unexpected failures encountered in many oxidation ponds.

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APPENDIX

Sludge Accumulation Section

Sludge Temperature and Reaction Coefficient

The following table gives the mean temperature for successive 5-day periods and the coefficient K for this temperature. This data was taken from the yearly temperature profile and is based on a 30 day month broken down into 5 day segments. The data starts on July 1 of any year.

Month	Period	Mean Temp. °C	Sludge Coefficient K^1	Liquid phase Coefficient K
July	1	21.3	.0085	.414
	2	22.6	.0090	.438
	3	23.5	.0094	.456
	4	23.7	.0095	.461
	5	23.3	.0093	.452
	6	22.7	.0091	.440
August	7	22.0	.0088	.426
	8	21.1	.0084	.410
	9	20.1	.0081	.392
	10	19.0	.0077	.372
	11	17.9	.0073	.354
	12	16.9	.0069	.338
September	13	15.9	.0065	.323
	14	15.0	.0063	.310
	15	14.2	.0060	.299
	16	13.5	.0058	.290
	17	12.8	.0056	.280
	18	12.2	.0055	.273
October	19	11.5	.0053	.264
	20	10.9	.0052	.256
	21	10.4	.0051	.251
	22	9.9	.0050	.245
	23	9.4	.0049	.240
	24	9.0	.0048	.235
November	25	8.6	.0047	.231
	26	8.2	.0046	.226
	27	7.9	.0046	.223
	28	7.6	.0045	.219
	29	7.4	.0045	.217
	30	7.2	.0044	.214
December	31	7.1	.0044	.213
	32	7.0	.0044	.212
	33	7.0	.0044	.212
	34	7.0	.0044	.212
	35	7.1	.0044	.213
	36	7.3	.0045	.215

Month	Period	Mean Temp. °C	Sludge Coefficient K^1	Liquid phase Coefficient K
January	37	7.6	.0045	.219
	38	7.8	.0046	.222
	39	8.1	.0046	.225
	40	8.3	.0047	.227
	41	8.6	.0047	.231
	42	8.9	.0048	.234
February	43	9.2	.0048	.237
	44	9.5	.0049	.240
	45	9.8	.0050	.244
	46	10.1	.0050	.247
	47	10.5	.0051	.252
	48	10.8	.0052	.255
March	49	11.1	.0052	.259
	50	11.4	.0053	.263
	51	11.7	.0054	.266
	52	12.1	.0055	.271
	53	12.4	.0055	.275
	54	12.7	.0056	.279
April	55	13.1	.0057	.285
	56	13.4	.0058	.288
	57	13.8	.0059	.294
	58	14.1	.0060	.298
	59	14.5	.0061	.303
	60	14.9	.0062	.309
May	61	15.2	.0063	.313
	62	15.6	.0064	.319
	63	15.9	.0066	.324
	64	16.3	.0067	.329
	65	16.7	.0068	.335
	66	17.1	.0070	.341
June	67	17.5	.0071	.347
	68	17.9	.0073	.354
	69	18.4	.0074	.362
	70	18.9	.0076	.370
	71	19.5	.0078	.380
	72	20.2	.0081	.394

Sample Calculation

Lagoon Temperature Predictions

Weather Station: Salem
Month: May
Average or Maximum: August
Trial Number: 1
Data & Computation:

$Q = 480$ ly/day
$u = 6.8$ mph
relative humidity = 75.8%
$T_a = 56.8^\circ F$
$e_a = 12.0$ mb
assumed $T_w = 60^\circ F$
$e_w = 17.7$ mb

$$480 - 3(60) - 1.3(6.8)(17.7-12.0) - 0.4(6.8)(60-56.8) + 0.631(50-60) \overset{?}{=} 216$$

$$480 - 180 - 50.3 - 8.7 - 6.31 \overset{?}{=} 216$$
$$233 = 216$$

OK ______, T_w = ______ °F

NG __x__, Try T_w = 62°F for next trial

Lagoon Temperature Predictions

Weather Station: Salem
Month: May
Average or Maximum: August
Trial Number: 2
Data & Computation:

$Q = 480$ ly/day
$u = 6.8$ mph
relative humidity - 75.8%
$T_a = 56.8^\circ F$
$e_a = 12.0$ mb
assumed $T_w = 62^\circ F$
$e_w = 19.0$ mb

$$480 - 3(62) - 1.3(6.8)(19.0-12.0) - 0.4(6.8)(62-56.8) + 0.631(50-62) \overset{?}{=} 216$$

Trial Number 2 (continued)

$480 - 186 - 62 - 14.1 - 7.6 \overset{?}{=} 216$

$210 = 216$

OK ______, T_w = ______°F

NG __x__, Try T_w = 61°F for next trial

Lagoon Temperature Predictions

Weather Station: Salem
Month: May
Average or Maximum: August
Trial Number: 3
Data & Computation:

Q = 480 ly/day
u = 6.8 mph
relative humidity = 75.8%
T_a = 56.8°F
e_a = 12.0 mb
assumed T_w = 61°F
e_w = 18.3 mb

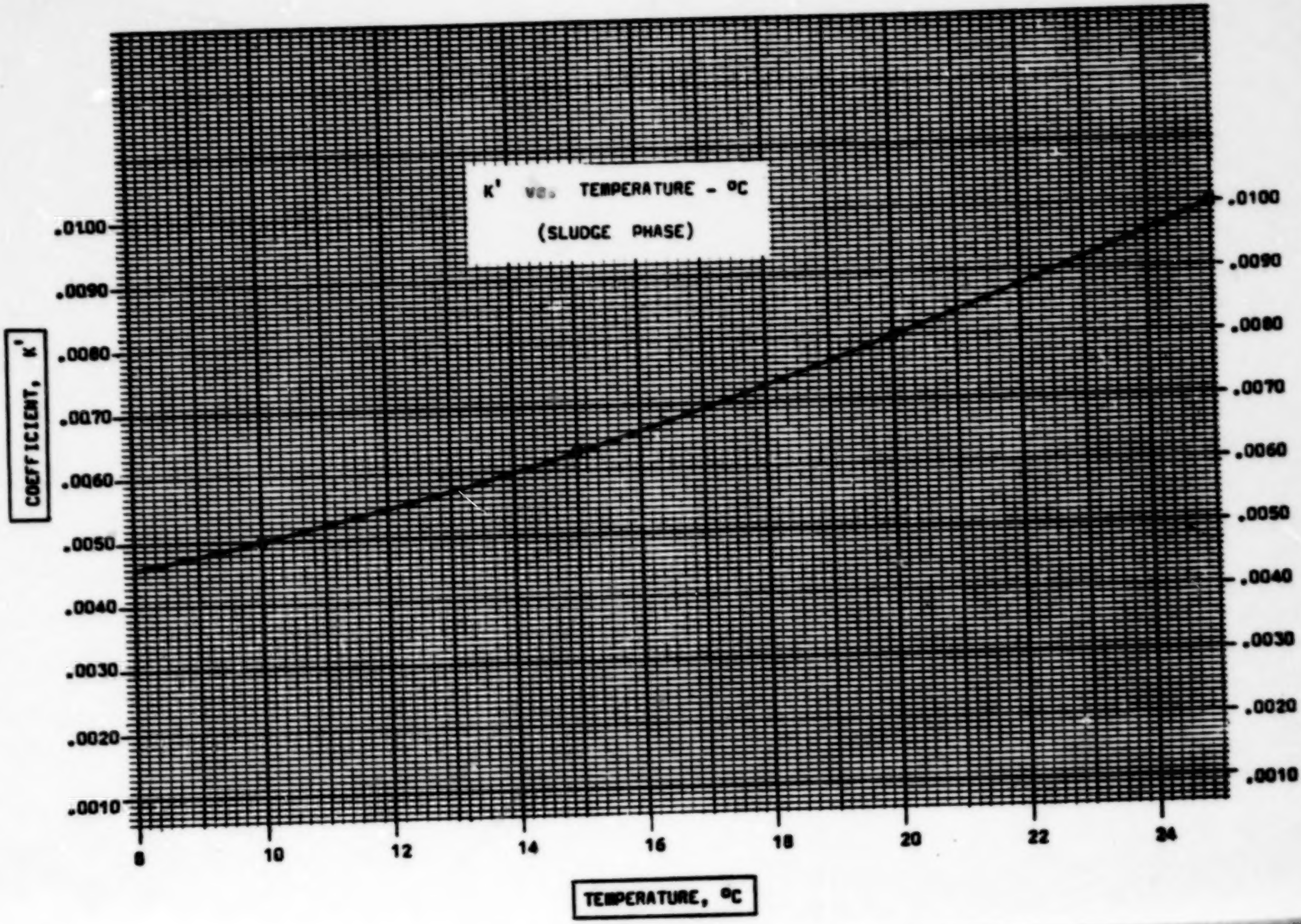
$480 - 3(61) - 1.3(6.8)(18.3-12.0) - 0.4(6.8)(61-56.8) + 0.631(50-61) \overset{?}{=} 216$

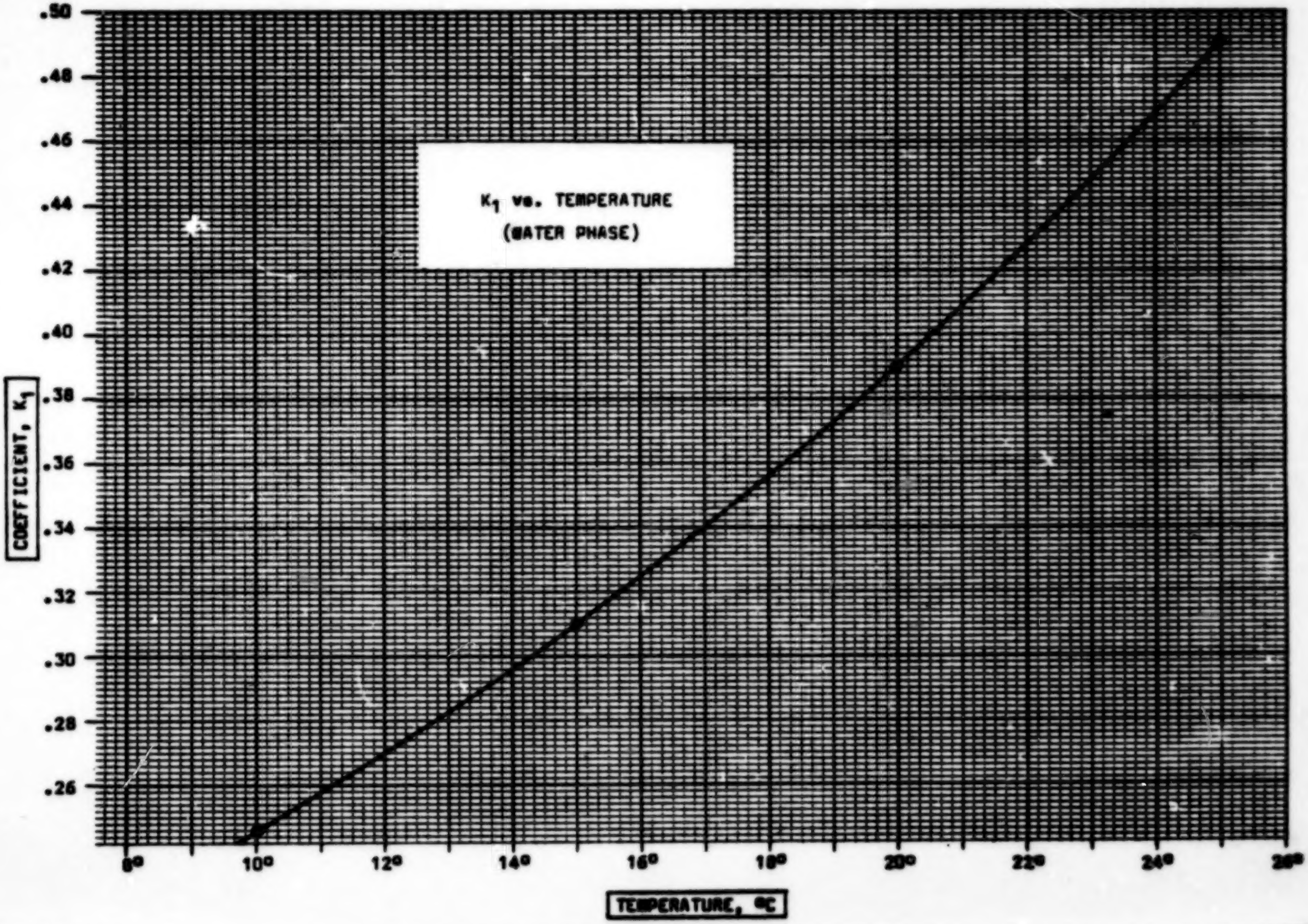
$480 - 183 - 55.5 - 11.5 - 6.9 \overset{?}{=} 216$

$223 = 216$

OK __X__, T_w = 61.5°F

NG ______, Try T_w = ______°F for next trial


K' vs. TEMPERATURE - °C
(SLUDGE PHASE)
COEFFICIENT, K'
.0100
.0090
.0080
.0070
.0060
.0050
.0040
.0030
.0020
.0010
TEMPERATURE, °C
8
10
12
14
16
18
20
22
24


K_1 vs. TEMPERATURE
(WATER PHASE)
COEFFICIENT, K_1
.50
.48
.46
.44
.42
.40
.38
.36
.34
.32
.30
.28
.26
8°
10°
12°
14°
16°
18°
20°
22°
24°
26°
TEMPERATURE, °C

First Run

Sludge Calculations

	(1) Period	(2) Rate %	(3) Initial sludge accumulation lbs BOD/acre	(4) Daily sludge O_2 demand lbs/acre/day	(5) Daily addition of sludge, lbs BOD/acre/day	(6) Final sludge accumulation lbs BOD/acre
July	1	1.95	406.0	7.9	7	401.6
	2	2.07	401.6	8.3		395.3
	3	2.16	395.3	8.5		388.0
	4	2.18	388.0	8.4		382.0
	5	2.14	382.0	8.1		376.4
	6	2.10	376.4	7.9		372.1
Aug.	7	2.02	372.1	7.5		368.6
	8	1.93	368.6	7.1		368.1
	9	1.86	368.1	6.9		368.7
	10	1.77	368.7	6.5		371.0
	11	1.68	371.0	6.3		374.7
	12	1.59	374.7	6.0		379.1
Sept.	13	1.50	379.1	5.7		385.5
	14	1.45	385.5	5.6		392.3
	15	1.38	392.3	5.5		400.0
	16	1.33	400.0	5.4		408.2
	17	1.29	408.2	5.3		416.6
	18	1.26	416.6	5.3		425.2
Oct.	19	1.22	425.2	5.2		434.0
	20	1.20	434.0	5.2		442.8
	21	1.17	442.8	5.2		451.7
	22	1.15	451.7	5.2		460.5
	23	1.13	460.5	5.2		469.6
	24	1.10	469.6	5.2		478.6
Nov.	25	1.08	478.6	5.2		487.6
	26	1.06	487.6	5.2		496.6
	27	1.06	496.6	5.3		505.1
	28	1.04	505.1	5.3		513.6
	29	1.04	513.6	5.4		521.7
	30	1.01	521.7	5.3		530.2
Dec.	31	1.01	530.2	5.4		538.2
	32	1.01	538.2	5.5		545.8
	33	1.01	545.8	5.5		553.2
	34	1.01	553.2	5.6		560.1
	35	1.01	560.1	5.7		566.6
	36	1.04	566.6	5.9		572.1

	(1)	(2)	(3)	(4)	(5)	(6)
Jan.	37	1.04	572.1	6.0	7	577.2
	38	1.06	577.2	6.1	↓	581.6
	39	1.06	581.6	6.2		585.6
	40	1.08	585.6	6.3		589.0
	41	1.08	589.0	6.4		592.0
	42	1.10	592.0	6.5		594.5
Feb.	43	1.10	594.5	6.6		596.7
	44	1.13	596.7	6.7		598.0
	45	1.15	598.0	6.9		598.5
	46	1.15	598.5	6.9		599.0
	47	1.17	599.0	7.0		599.0
	48	1.20	599.0	7.2		598.0
Mar.	49	1.20	598.0	7.2		597.0
	50	1.22	597.0	7.3		595.5
	51	1.24	595.5	7.4		593.5
	52	1.27	593.5	7.5		591.0
	53	1.27	591.0	7.5		588.5
	54	1.29	588.5	7.6		585.5
April	55	1.31	585.5	7.7		582.2
	56	1.31	582.2	7.7		578.7
	57	1.36	578.5	7.8		574.5
	58	1.38	574.5	7.9		570.0
	59	1.40	570.0	8.0		565.2
	60	1.43	565.2	8.1		559.9
May	61	1.45	559.9	8.1		554.5
	62	1.47	554.5	8.1		548.9
	63	1.52	548.9	8.3		542.5
	64	1.54	542.5	8.3		535.9
	65	1.56	535.9	8.3		529.3
	66	1.61	529.3	8.5		521.9
June	67	1.63	521.9	8.5		514.6
	68	1.63	514.6	8.6		506.7
	69	1.70	506.7	8.6		498.9
	70	1.75	498.9	8.7		490.6
	71	1.79	490.6	8.7		482.1
	72	1.86	482.1	8.9		472.5

Second Run

Sludge Calculations

	(1) Period	(2) Rate %	(3) Initial sludge accumulation lbs BOD/acre	(4) Daily sludge O_2 demand lbs/acre/day	(5) Daily addition of sludge, lbs BOD/acre/day	(6) Final sludge accumulation lbs BOD/acre
July	1	1.95	472.5	9.1	7	464.8
	2	2.07	464.8	9.5	↓	452.2
	3	2.16	452.2	9.7		438.5
	4	2.18	438.5	9.4		426.3
	5	2.14	426.3	9.0		416.2
	6	2.10	416.2	8.7		407.9
Aug.	7	2.02	407.9	8.2		402.0
	8	1.93	402.0	7.7		398.4
	9	1.86	398.4	7.4		396.8
	10	1.77	396.8	7.0		396.8
	11	1.68	396.8	6.7		398.3
	12	1.59	398.3	6.4		400.5
Sept.	13	1.50	400.5	6.0		405.3
	14	1.45	405.3	5.9		410.7
	15	1.38	410.7	5.7		417.2
	16	1.33	417.2	5.6		424.3
	17	1.29	424.3	5.5		431.7
	18	1.26	431.7	5.5		439.3
Oct.	19	1.22	439.3	5.4		447.2
	20	1.20	447.2	5.4		455.1
	21	1.17	455.1	5.4		463.3
	22	1.15	462.2	5.4		471.5
	23	1.13	471.5	5.4		479.7
	24	1.10	479.7	5.3		488.1
Nov.	25	1.08	488.1	5.3		496.5
	26	1.06	496.5	5.3		504.9
	27	1.06	504.9	5.4		512.9
	28	1.04	512.9	5.4		521.0
	29	1.04	521.0	5.5		528.7
	30	1.01	528.7	5.4		536.8
Dec.	31	1.01	536.8	5.5		544.5
	32	1.01	544.5	5.5		551.9
	33	1.01	551.9	5.6		558.9
	34	1.01	558.9	5.7		565.5
	35	1.01	565.5	5.7		571.8
	36	1.04	571.8	6.0		576.9

	(1)	(2)	(3)	(4)	(5)	(6)
Jan.	37	1.04	576.9	6.0	7	581.8
	38	1.06	581.8	6.2		585.8
	39	1.06	585.8	6.2		589.7
	40	1.08	589.7	6.4		592.7
	41	1.08	592.7	6.4		595.7
	42	1.10	595.7	6.6		597.7
Feb.	43	1.10	597.7	6.6		599.7
	44	1.13	599.7	6.8		600.7
	45	1.15	600.7	6.9		601.2
	46	1.15	601.2	6.9		601.7
	47	1.17	601.7	7.0		601.7
	48	1.20	601.7	7.2		600.7
Mar.	49	1.20	600.7	7.2		599.7
	50	1.22	599.7	7.3		598.2
	51	1.24	598.2	7.4		596.2
	52	1.27	596.2	7.6		593.4
	53	1.27	593.4	7.5		590.9
	54	1.29	590.9	7.6		587.9
April	55	1.31	587.9	7.7		584.4
	56	1.33	584.4	7.8		580.6
	57	1.36	580.6	7.9		576.1
	58	1.38	576.1	7.9		571.5
	59	1.40	571.5	8.0		566.6
	60	1.43	566.6	8.1		561.2
May	61	1.45	561.2	8.1		555.7
	62	1.47	555.7	8.1		550.0
	63	1.52	550.0	8.3		543.4
	64	1.54	543.4	8.3		536.8
	65	1.56	536.8	8.3		530.1
	66	1.61	530.1	8.5		522.7
June	67	1.63	522.7	8.5		515.4
	68	1.68	515.4	8.6		507.3
	69	1.70	507.3	8.6		499.5
	70	1.75	499.5	8.7		491.1
	71	1.79	491.1	8.7		482.4
	72	1.86	482.4	8.9		472.9

Liquid Phase Calculations

In this step the liquid phase BOD concentration and the daily BOD of this portion will be calculated using the theoretical temperature profile and the K rates derived therefrom. Assumed loading rate equals 21 lbs. of BOD per acre per day of which 7 lbs. is settleable. To determine a starting concentration an average K rate for June will be calculated and a concentration used such that the demand from this concentration just equals the 14 lbs/acre/day being added.

Starting condition:

$$\frac{dL}{dt} = -KL \text{ with } \frac{dL}{dt} = 14 \text{ lbs BOD/acre/day}$$

$$K = .368 \text{ (average for June)}$$

$$L = \frac{14}{.368} = 38 \text{ lbs BOD/acre}$$

Calculations

(1) Period	(2) K	(3) Initial BOD concentration lbs/BOD/acre	(4) Daily O_2 demand lbs/acre/day	(5) Daily BOD addition lbs/acre/day	(6) Final BOD accumulation lbs BOD/acre	(7) mg/L
July 1				14		
2	.438	34.1	14.4		32.1	3.92
3	.456	32.1	14.3		30.8	3.76
4	.461	30.8	14.1		30.4	3.72
5	.452	30.4	13.9		30.9	3.78
6	.440	30.9	13.8		31.8	3.88
Aug. 7	.426	31.8	13.8		32.8	4.01
8	.410	32.8	13.7		34.1	4.18
9	.392	34.1	13.7		35.6	4.36
10	.372	35.6	13.6		37.5	4.59
11	.354	37.5	13.6		39.3	4.82
12	.338	39.3	13.6		41.1	5.04
Sept. 13	.323	41.1	13.6		43.0	5.27
14	.310	43.0	13.6		44.8	5.50
15	.299	44.8	13.7		46.5	5.70
16	.290	46.5	13.7		48.0	5.89
17	.280	48.0	13.7		49.6	6.08
18	.273	49.6	13.7		50.9	6.25
Oct. 19	.264	50.9	13.7		52.6	6.46
20	.256	52.6	13.7		54.2	6.65
21	.251	54.2	13.8		55.4	6.80
22	.245	55.4	13.7		56.7	6.95
23	.240	56.7	13.8		57.9	7.10
24	.235	57.9	13.8		59.1	7.25
Nov. 25	.231	59.1	13.8		60.2	7.38
26	.226	60.2	13.8		61.4	7.54
27	.223	61.4	13.8		62.4	7.65
28	.219	62.4	13.8		63.5	7.78
29	.217	63.5	13.9		64.2	7.87
30	.214	64.2	13.8		65.1	7.98
Dec. 31	.213	65.1	13.9		65.5	8.02
32	.212	65.5	13.9		65.9	8.08
33	.212	65.9	14.0		65.9	8.08
34	.212	65.9	14.0		65.9	8.08
35	.213	65.9	14.0		65.9	8.08
36	.215	65.9	14.1		65.4	8.01

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Jan. 37	.219	65.4	14.2	14	64.4	7.90
38	.222	64.4	14.2		63.5	7.78
39	.225	63.5	14.2		62.6	7.68
40	.227	62.6	14.1		61.9	7.59
41	.231	61.9	14.2		61.0	7.48
42	.234	61.0	14.2		60.1	7.38
Feb. 43	.237	60.1	14.1		59.4	7.29
44	.240	59.4	14.2		58.6	7.18
45	.244	58.6	14.2		57.7	7.08
46	.247	57.7	14.2		56.9	6.98
47	.252	56.9	14.2		55.9	6.86
48	.255	55.9	14.2		55.1	6.77
Mar. 49	.259	55.1	14.2		54.3	6.66
50	.263	54.3	14.2		53.5	6.57
51	.266	53.5	14.1		52.9	6.50
52	.271	52.9	14.2		51.9	6.37
53	.275	51.9	14.2		51.1	6,27
54	.279	51.1	14.1		50.4	6.18
Apr. 55	.285	50.4	14.2		49.3	6.05
56	.288	49.3	14.1		48.7	5.98
57	.294	48.7	14.2		47.8	5.86
58	.298	47.8	14.1		47.2	5.79
59	.303	47.2	14.2		46.3	5.67
60	.309	46.3	14.2		45.4	5.57
May 61	.313	45.4	14.1		44.8	5.50
62	.319	44.8	14.2		44.0	5.40
63	.324	44.0	14.1		43.3	5.31
64	.329	43.3	14.1		42.7	5.24
65	.335	42.7	14.2		41.9	5.14
66	.341	41.9	14.1		41.2	5.05
June 67	.347	41.2	14.2		40.4	4.95
68	.354	40.4	14.2		39.6	4.86
69	.362	39.6	14.2		38.8	4.76
70	.370	38.8	14.2		37.9	4.64
71	.380	37.9	14.2		36.9	4.52
72	.394	36.9	14.2		35.7	4.37
July 1	.414	35.7	14.4	14	33.9	4.15
2	.438	33.9	14.4		32.1	
3	.456	32.1				
4	.461					
5	.452					
6	.440					
7	.426					

APPENDIX D

PLANKTON ENUMERATION

Plankton samples were collected from 6 inches below the surface at the point of discharge of the two cells. A specie determination and count of the phytoplankton was made under a 100-power microscope with the aid of a nannoplankton counting slide. Portions of these same samples were then placed in a centrifuge and turned at 3000 rpm for 15 minutes. The residue was then measured and recorded as solid volume ml/100 ml. Figure 1-D illustrates a typical population.

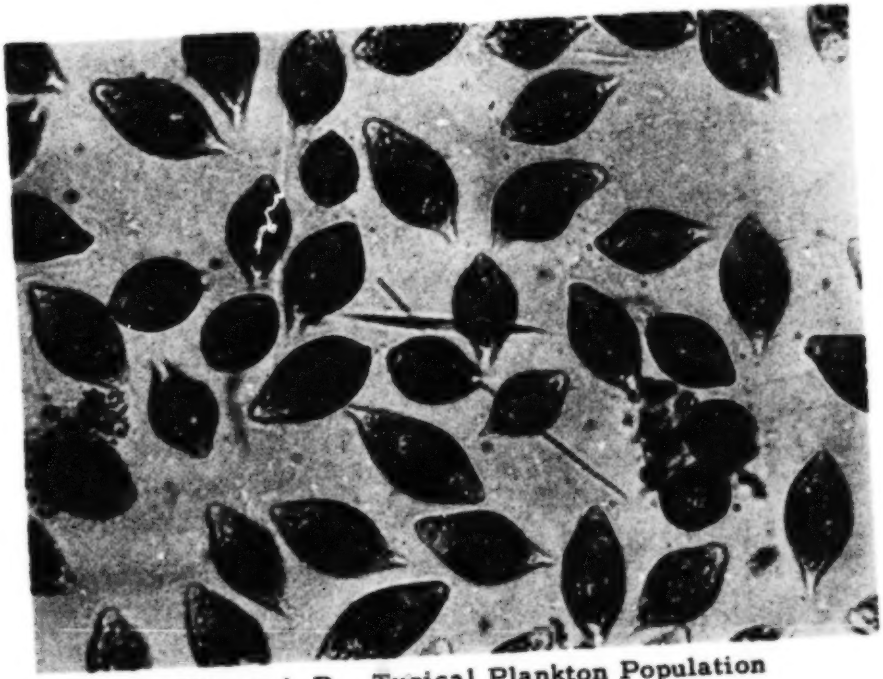


Figure 1-D. Typical Plankton Population

Wet volumes and predominate species are listed in Table 1D.

Table 1D

Month	Predominate Species	Wet Vol. of all Species ml/100ml
January	ESG	0.04
February	ECG	0.05
March	ES	0.04
April	MES	0.11
May	MBR	0.13
June	BSE	0.09
July	BSE	0.08
August	BEC	0.14
September	BES	0.25
October	BSR	0.15
November	BSG	0.08
December	SGB	0.03

Key

B - Chlorella
C - Chloregonium
E - Euglena
G - Uncoded Green
M - Micratinium
S - Scenedesmus
R - Rotifera

APPENDIX E

NITROGEN AND PHOSPHATE VARIATIONS AND BOD TIME RELATIONSHIPS FOR RIVER MODEL STUDIES

Curves 1-E through 7-E represent nitrogen and phosphate transformation as well as BOD-time results as obtained from studying the effects of effluent on receiving streams. Information shown was collected from the river model study described in the section on "Effects of Effluent on Receiving Streams" starting on page 59.

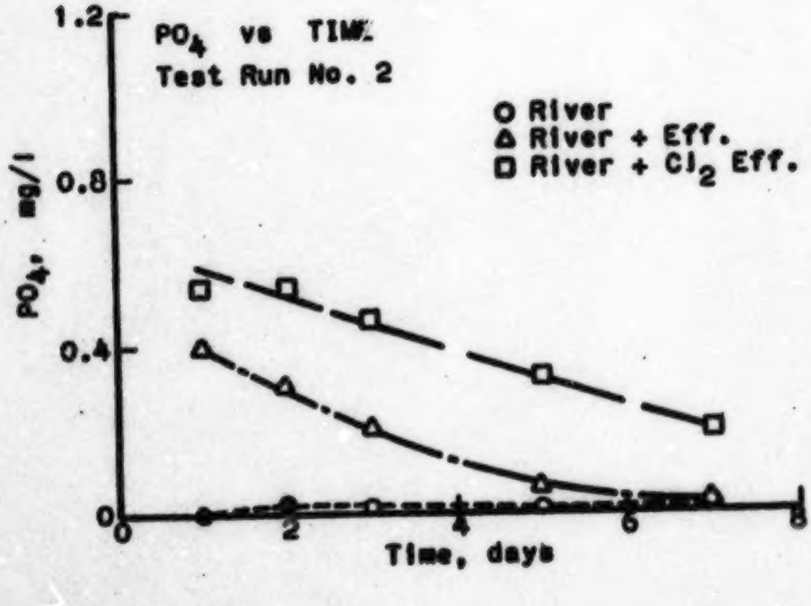


Figure 1-E. Phosphate Variations

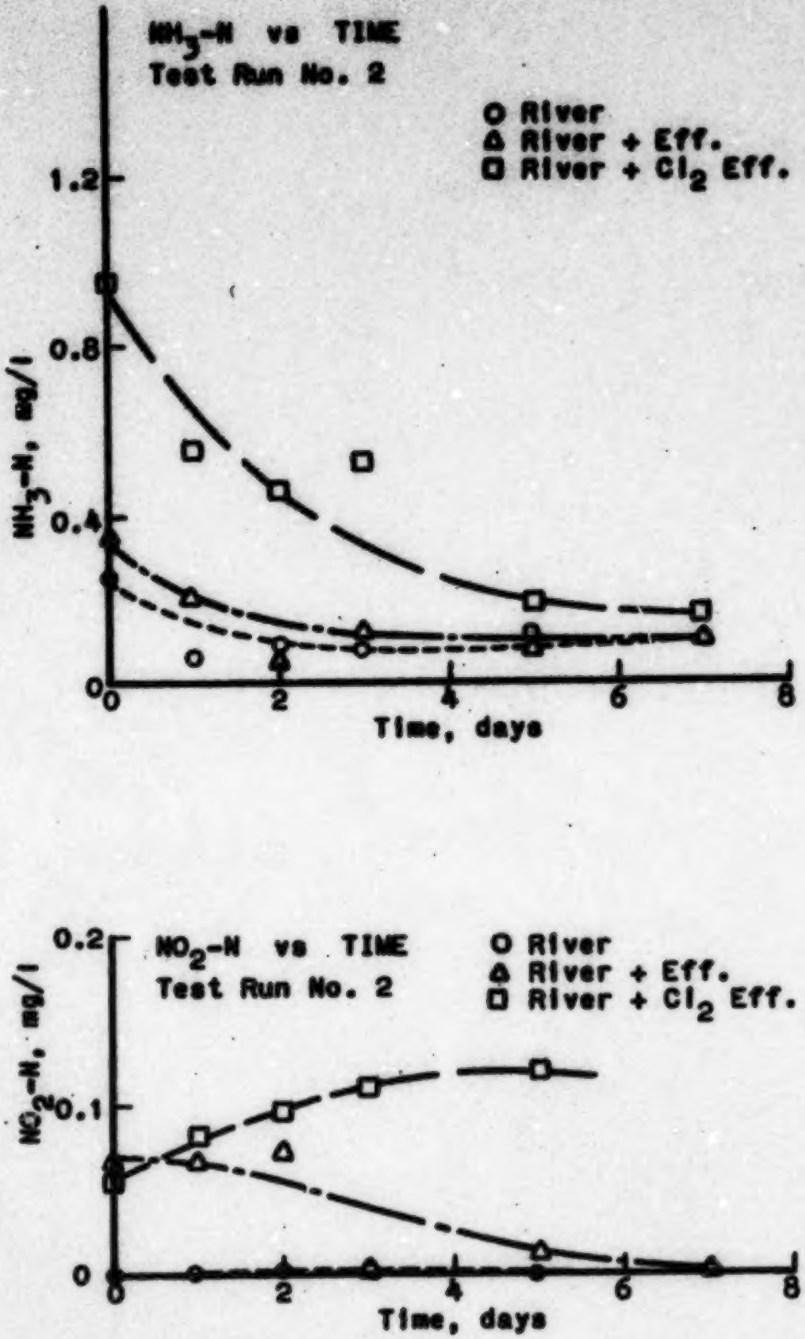


Figure 2-E. Ammonia-Nitrate Nitrogen Variations

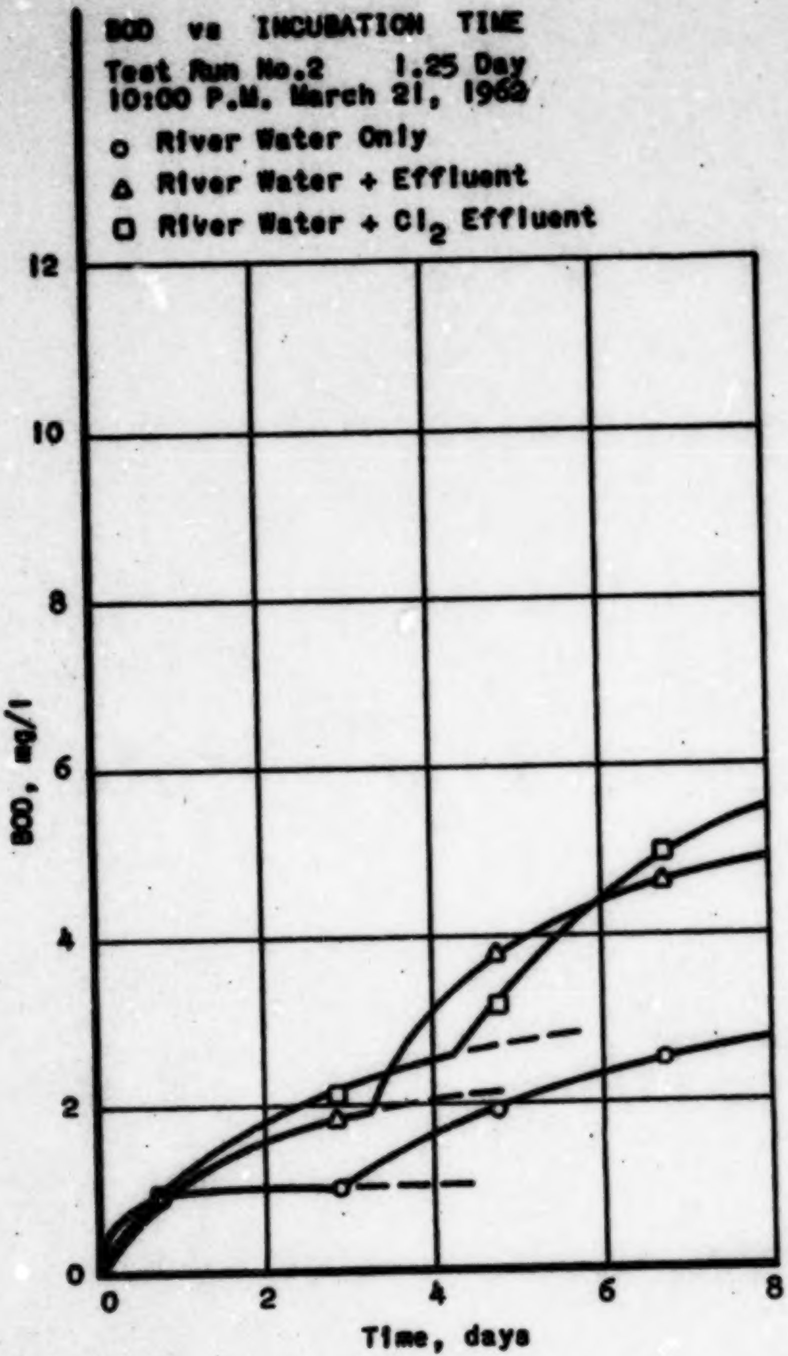


Figure 3-E. BOD - Time Relationship
Sample Collected at Time Indicated

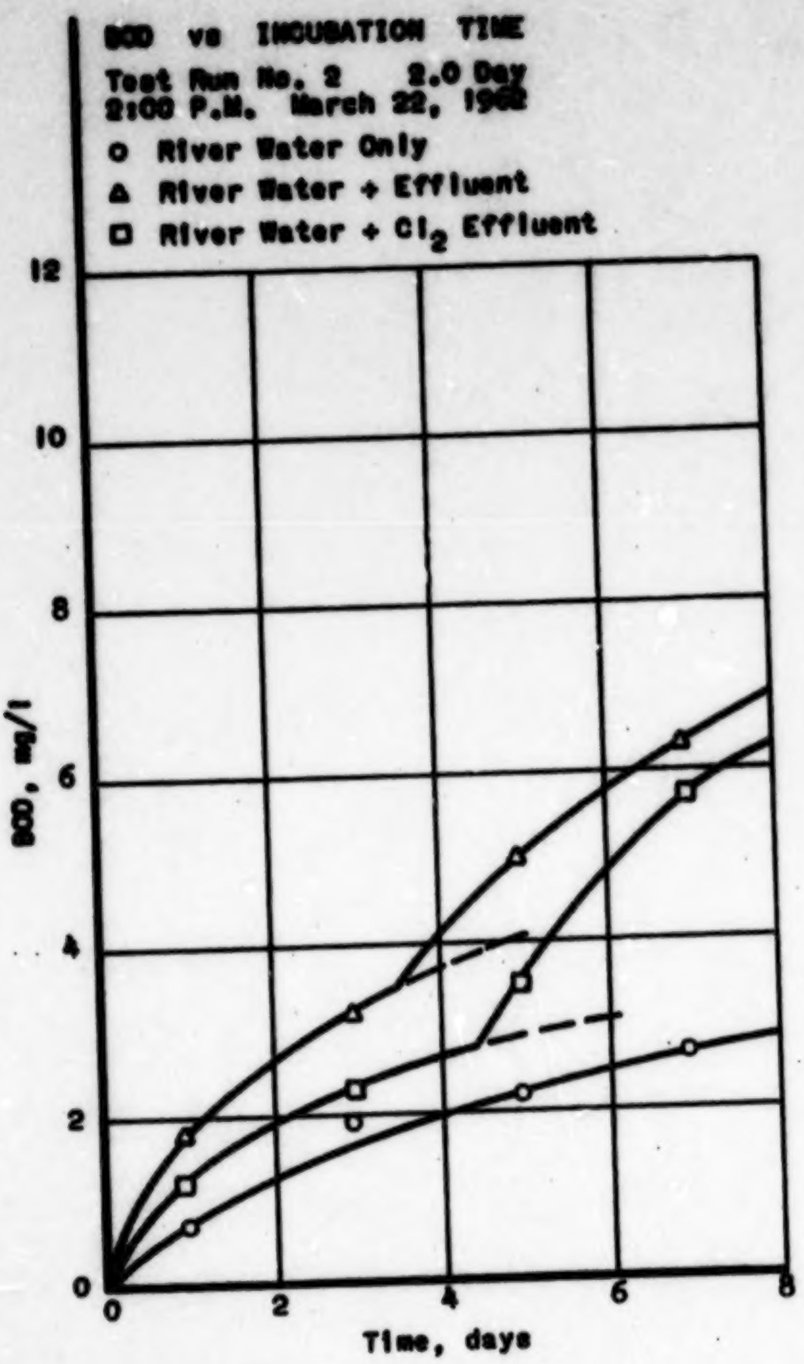


Figure 4-E. BOD - Time Relationship
Sample Collected at Time Indicated

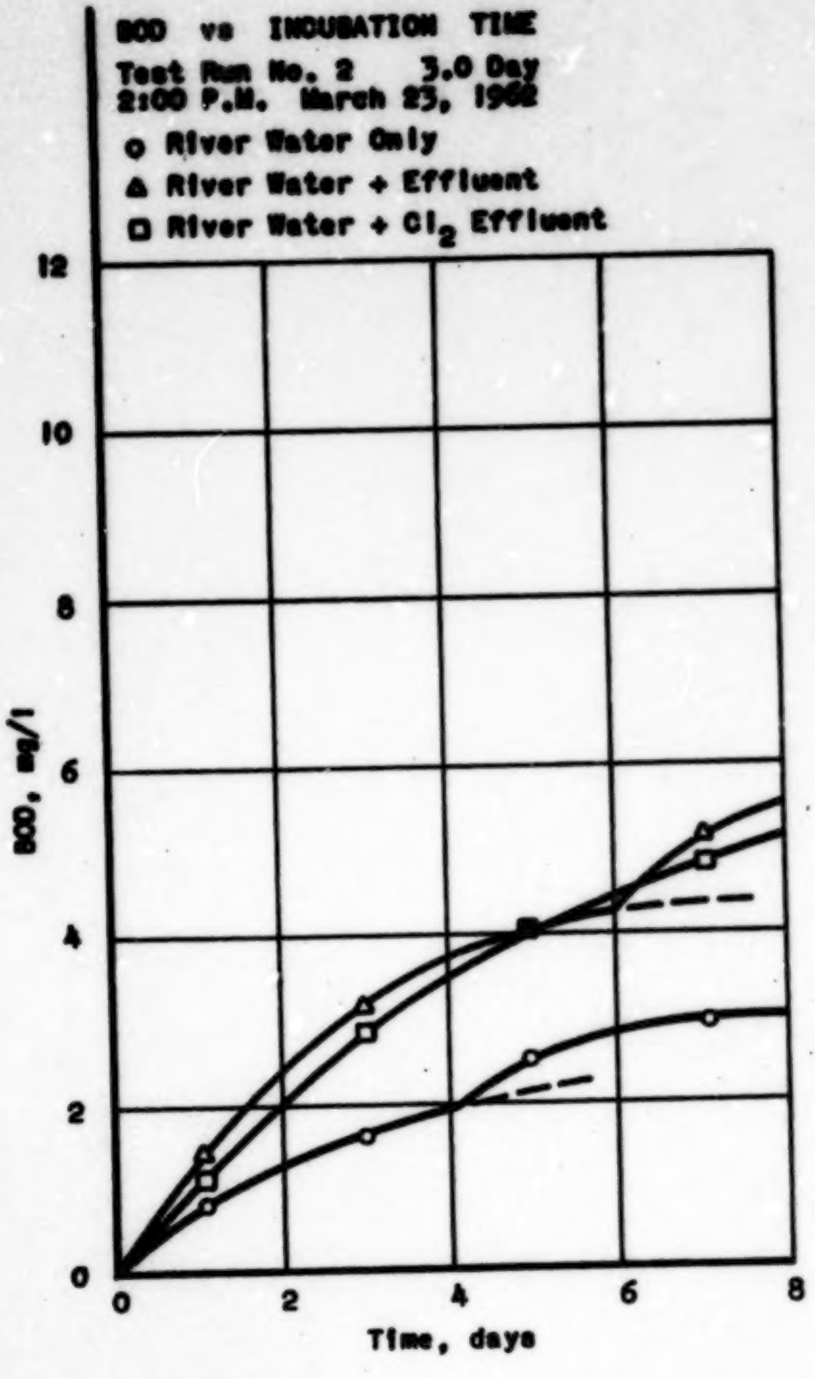


Figure 5-E. BOD - Time Relationship
Sample Collected at Time Indicated

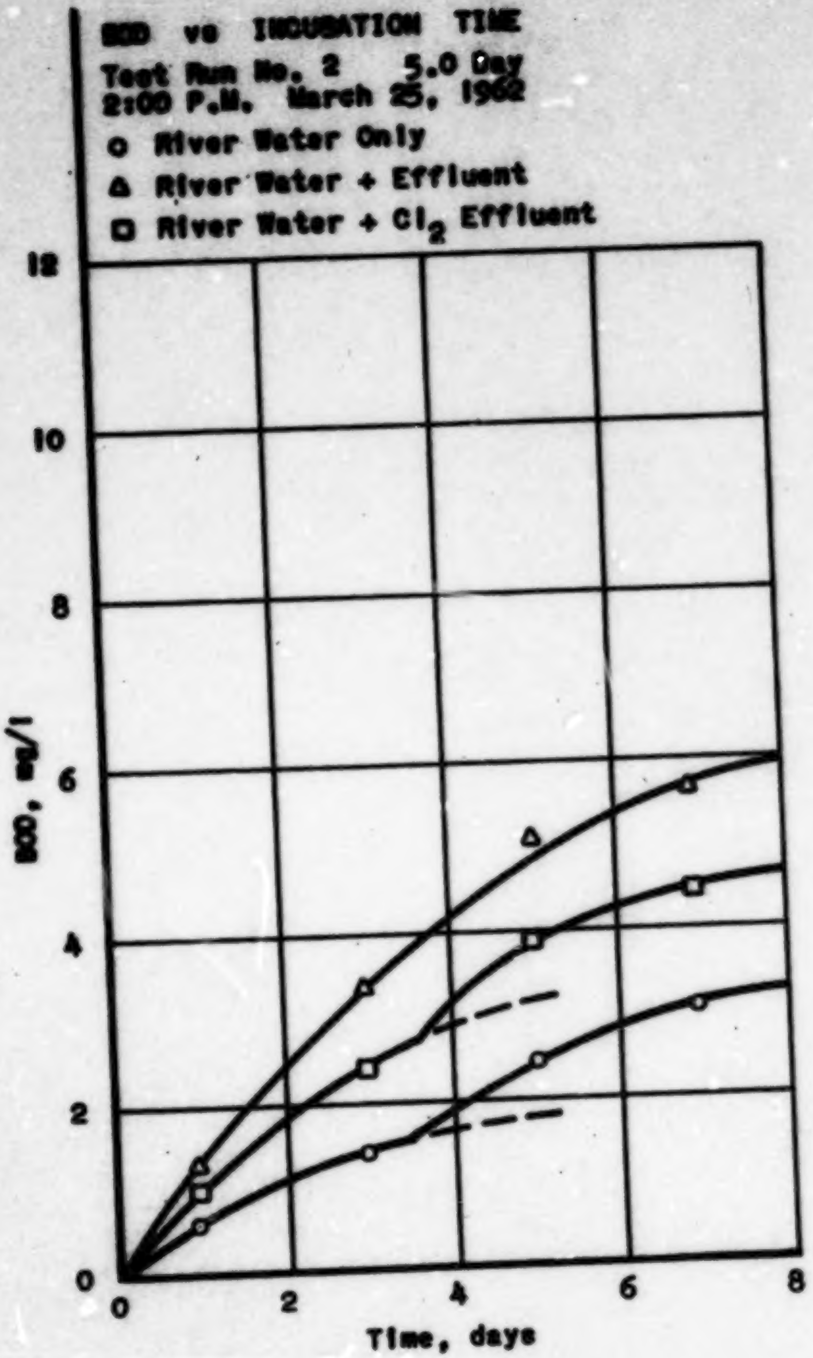


Figure 6-E. BOD - Time Relationship
Sample Collected at Time Indicated

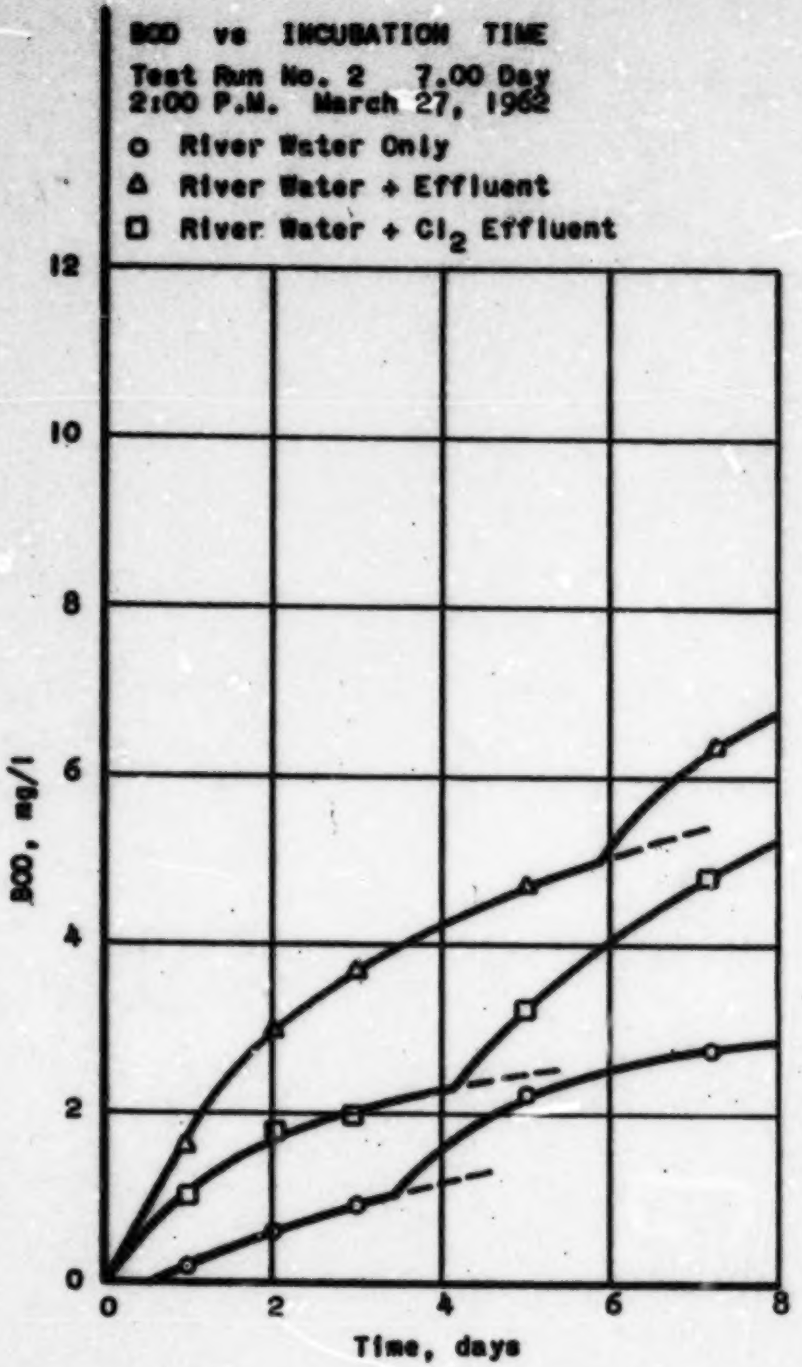


Figure 7-E. BOD - Time Relationship
Sample Collected at Time Indicated

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